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TITOLO TESI / THESIS TITLE

BOREHOLE STABILITY IN ROCK SALT

Cognome / Surname AL SODANY Nome / Name WALID KHALED

Matricola / Registration number 788821

Tutore / Tutor: GIOVANNI BATTISTA CROSTA

Cotutore / Co-tutor: MATTEO ORYEM CIANTIA

Supervisor: RICCARDO CASTELLANZA

Coordinatore / Coordinator: MARIA LUCE FREZZOTTI

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Abstract

Rock salt represents a relevant resource for storage and barrier of hydrocarbon reservoirs due to its special mechanical properties; as a consequence many efforts are carried out to understand the mechanical behaviour. On the other hand, the deformation of the rock salt is markedly time dependent. This feature often has a negative influence on the stability of borehole crossing this formation. In fact it is common to reach collapse of the casing pipe in deep boreholes of oil well.

The aim of the this thesis is to study the stability of borehole in rock salt by creating a new hollow cylinder apparatus suitable to simulate a problem in oil well crossing a rock salt formation. After a standard geomechanical characterization of rock salt, the new apparatus was conceived, design and built. A relevant calibration process was required to get feasible results. Experimental results in the new apparatus were obtained. By adopting empirical, analytical and numerical models the results were simulated and a theoretical and numerical approach to face the borehole instability in rock salt formation is proposed

Key words: *borehole instability, rock salt, creep, dilatancy boundary, hollow cylinder experiments, constitutive models, visco-plastic, rheology of rock salt, casing collapse*

Contents

Chapter 1: Definition of the problem

1.1. Introduction

The borehole wall stability problem is particularly important, because it connect with strategically projects, as: oil wells, and caverns which, cover different purposes as: radioactive waste materials or reserve gas, and lately electricity generation.

It economically affect, as well environmentally, even every sector had have speciality to deal with this problem, but both of them are agreed that mechanical properties of rock the main reason behind it. Furthermore, other different factors play big role on this problem, which increase complexity, and leads for high cost results, starting from loss the borehole, or block the progressing of the oil well drilling, and sometime the risk will be developed that lead to abandonment the oil well, for instance, (50,000-100,000) $, it's the cost for one day of drilling operations for onshore oil well.

The manifestations of this problem represent by sticking drilling pipes, failing cementing operations, and collapsing the casing of borehole, all that is came by salt loading or rock collapsing.(see figure 1-1).

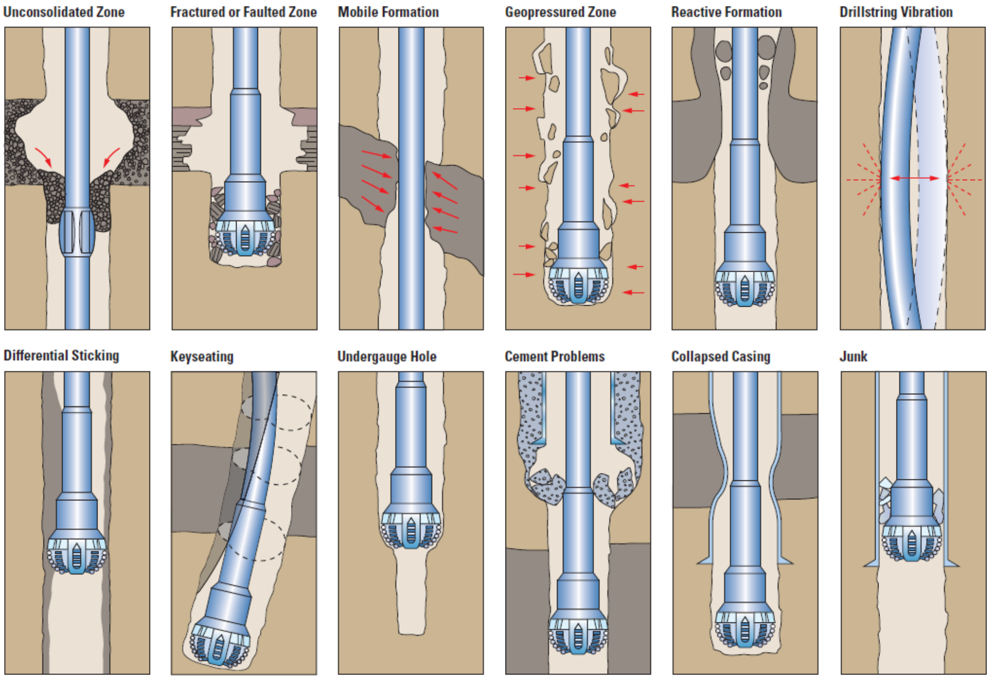


Figure 1-1borehole stability patterns in oil well

So, the figure has shown different cases which are connected by borehole stability, the interesting cases are plastic formations as rock salt, which has shared some types of shale.

The rock salt deformation extremely show depending time behaviour, the main part of this deformation is creep, that can generally classified to transient, steady state, and or tertiary.

The transient deformation usually happens at the first variation in the stresses which lead to change in shape of rock material with a rate of distortion (high creep rate) decreasing with time. Then the rock salt material enter in the secondary creep, at constant sufficient load and temperature which is characterized by constant deformation rate, and when it will accelerated ,the rock material will be entered in tertiary creep . This creep led to failed state.

There are other factors which effect on the rate of deformation as: mineral composition, burial depth, confining pressure, grain size, presence of inclusion of free water or free gas bubbles, and presence of impurities (clay or anhydrite).

The creep of plastic formation considers the main reason for collapsing pipes (drill pip or casing pipe) during or after finishing drilled a borehole.

1.2. Collapse of casing in rock salt formation.

Casing of borehole operation consider one of the important step in sequence drilling operations, so after complete a borehole, was cased and cemented to prepare for next hole. The casing pipe is designed to do different tasks, one of them is supported the rock deformations as plastic shale or rock salt however, this load depends on the underground conditions or technical operations for the oil well, and might be leading to overcoming the maximum designed value of the casing pipes, and then lead to collapse.

The load also depends on the geometry of borehole, see figure (1-2), part of published researches were instructed the collapsing of the casing to the non-uniform loading a companied with exhausting the casing, that decrease the thickness, and then will led decrease resistance (Lin. et al., 2013). Certainly, the main reason stands behind, depends on the in situ stresses, which effect on the casing pipes, that load effect uniformly, other non-uniform, as well shearing, the non-uniform loads depend on many factors:

- Borehole quality
- Eccentricity of casing
- Quality of cement
- Inter-bedded harder rocks (anhydrite) with soft rock salt
- Tortuosity
- Wearing casing

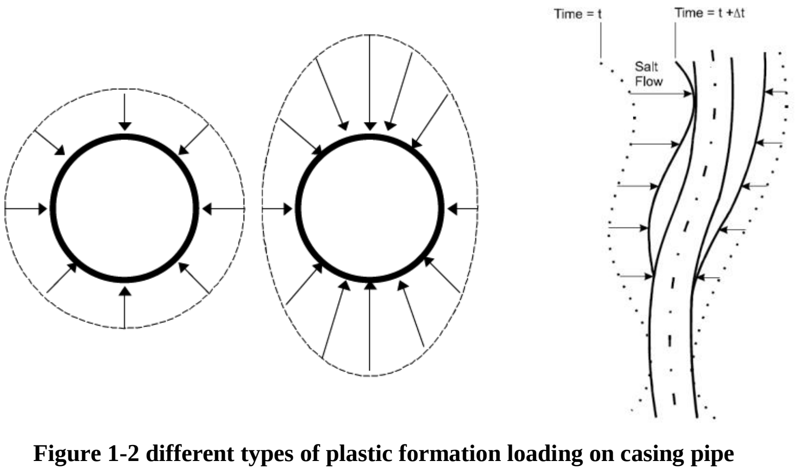


Figure 1-2 different types of plastic formation loading on casing pipe

The oil industry, specifically drilling operations, as well during the oil well life in completion or work-over operation, face this type of problem, which connected directly in borehole stability. Different oil companies through worldwide have been facing this problem, despite the excellent improvements and using the new technologies.

The rock salt has been considering a big challenge for drilling sector of the Iraqi oil industry. There are different cases that have been facing during drilling operations, completion, work-over and along well production life , it will review the most important cases for studying, and have been trying to re-produce one of them ,that would be agreement with the best "boundary value problems" experiment .

Generally, it can use a tri-axial test to simulate to some extent tunnels excavation or drilling oil wells. On the other hand , to build a good predication model depending on the experiment of " boundary value problem" ,will be more precisely than standard experiments, because the experiments of " boundary value problem" will be very close to describe all parameters that are needed in the mathematical or numerical models.

The histories of oil wells as mention previous have shown different cases for study, which reflect the concerned difficulties. These difficulties appear because there are lot of variables which are considered as the base for every experimental and theoretical model.

So, the good model should give best fitting and agreement with the experimental parts, and later gives the best solution for the case study.

The main target of the casing pipes is to cover and isolate different types of rocks which face during drilling borehole. The casing stage is one from different stages in drilling oil well operations, what we want to show here, that the casing pipes front of the rock salt are suffered by hard loading especially that accompanied with bad cementing operations.

Farther more, there are complexities as natural fractures, faults and interbedding with other types of rocks as shale, anhydrite and Gypsum. These complexity is came from different types of loading in very restricted zone of the casing pipe, might be created sharp edge on casing pipe.

Generally, it has been explained the case study of salt rock, which was covered by casing that was covered by sheath of bad cement.

1.3. Main sources for collapse casing in rock salt formation.

The borehole stability in oil well is very complicated issue because there are many factors behind it, as it was mention before.

For the Iraqi case study, the main factor responsible for the casing collapse front of salt rock is the bad cementing sheath. Farther more, the sufficient stresses as well presence the inter-bedded with harder rocks (anhydrite) and more, the temperature, and humidity etc.

From geo-mechanical point of view, the best step to follow it, is to know which the stress path, distribution of the in situ stresses as well temperature, and then draw outline for the casing collapse problem.

As it as mention, the main step after drilled the borehole is to cover, as soon as possible. However, the area of the case study (the south of Iraq), is characterized by types of formations (different types of shale) which have a high pore pressure. These rocks have given this geological section a special attention from drilling point of view. The practical point that was used to drill this section is to decrease the time for exposing these rocks (shale & salt) to the drilling mud.

So the two key points (isolate high pressure zone & prevent communications) are used by all companies which execute have been drilling there.

As it can see, from figure (1-3), the rocks are under high pressure, as well the complexities of the area , part is in high tectonic area (near to Zagros belt).however other part far from tectonic area, but still it has suffered from collapsing casing by creep of the salt rock.

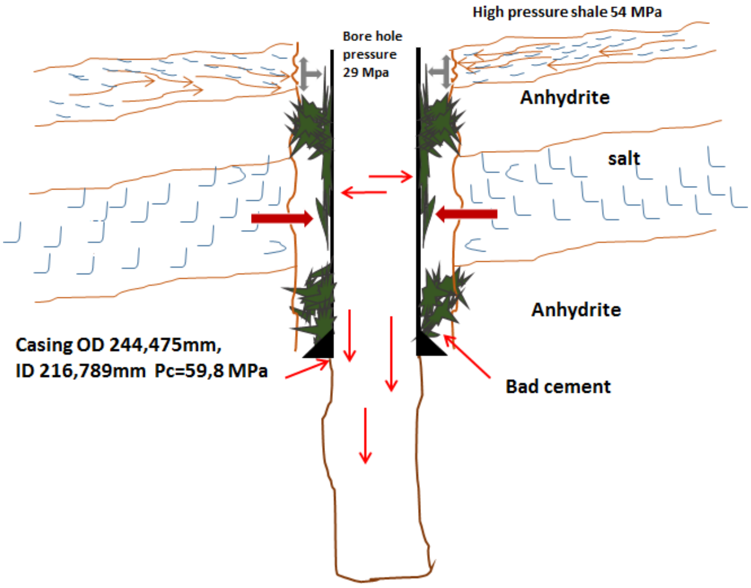


Figure 1-3 schematic for case study

The figure has shown summary for most variables that act on the casing collapse, one part of casing has exposed to the pure plastic flow of salt rock(creeping), while other part has faced shearing load because the inter-bedded rock salt with other types of rocks, and finally the casing has faced also different types of shale problem, (plastic shale), because some shale, will fall down in the borehole , and it might be causing drilling problems ,other type of shale will cause changing in the chemical properties of the drill mud .

So, in this thesis, the pure creeping salt was studied trying to find solution for this problem by studying mechanical properties of rock salt.

The area of interesting, is widespread in different oil fields, which have contained the same stratigraphic section but with different thicknesses of rock salt and other types of rocks, and the depth of this section differ from field to other. See figure (1-4).

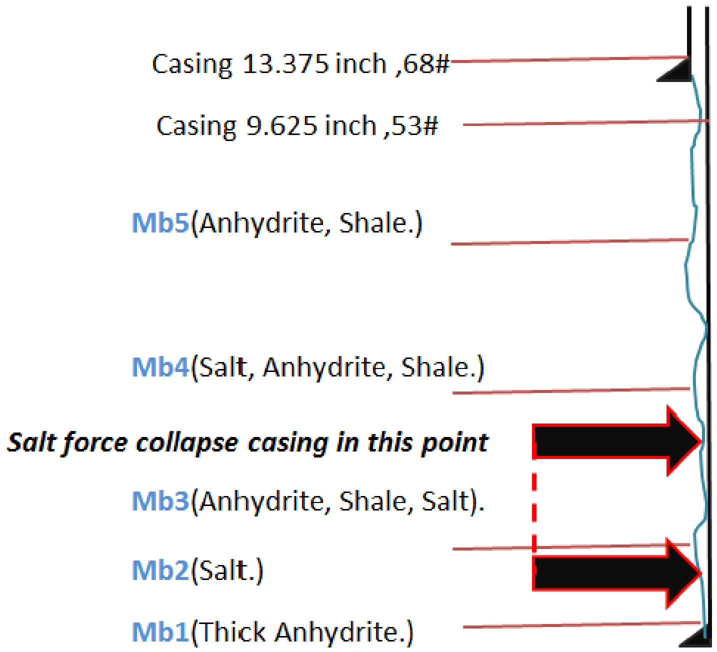


Figure 1-4 rock type's distribution in borehole drilled section

For instance , the thickness of the unit (MB2) reach to 50 meter in one of the oil field, and (20)meter in another, but both of them share the difficulties' during drilling this section (lower fars). Statistic's view between two fields was done for how many success oil wells that were done comparison with other wells which had been drilled hardly. See figure (1-5).

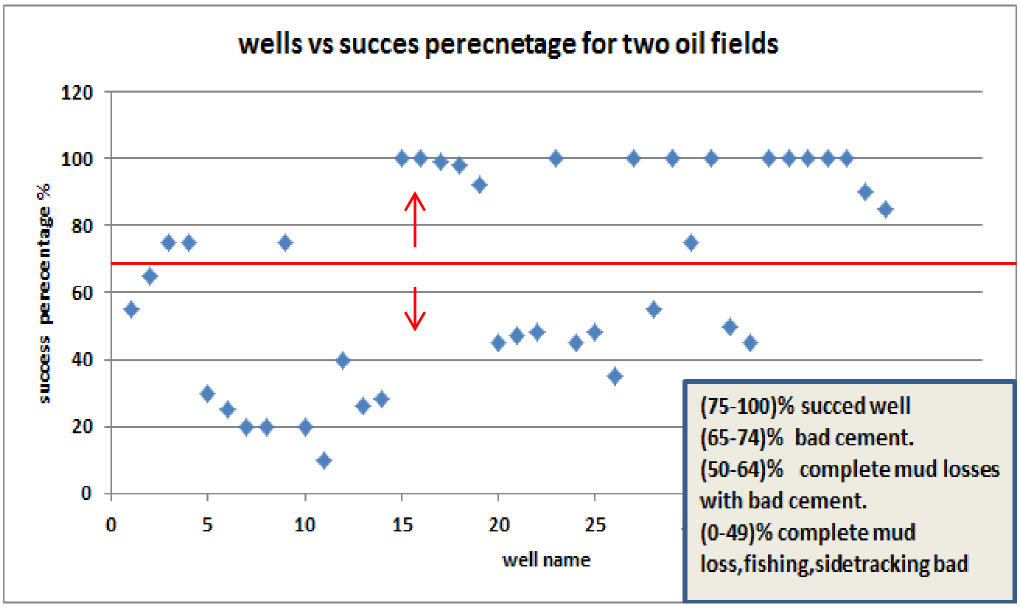


Figure 1-5 statistic view for drilled oil well through salt section

The figure has shown approximately 50% of drilled wells, which have the same problem (complete mud losses, bad cement, and collapse the casing) of the same section (lower Fars), and the survey was done just for two oil fields.

So, here, it can see a big challenging for the companies whom work there from economical point of view. The general practise using there, is to increase the drilling mud weight in order to support the borehole wall by confining pressure, which sometime it help, and other not. The reason for that, there are not enough geo-mechanical studies that can cover this area, beside that there are other factors that should be covered through these studies as chemical or temperature and others.

Other statistics surveyed has been done, to show the effect of increasing mud weight on borehole problems. See figure (1-6) . All figures, related to the (lower

Fras), which consist, of rock salt, shale, and anhydrite, as mention before. It can see, when the oil well had been drilled with high initial drilling mud weight the problems will be less compare with low initial drilling mud weight, farther more it is interesting to see the hole size had been changed for the same mud weight of three wells, that has reflected contribution other factors (complexity), while the general trend has shown less borehole changed when increasing mud weight but just for one well.

The complexity of the problem is clear, so it should be simplified without be a far from real variable that causes the problems. So, it is necessary to extract shared effect factors through all cases studies, to put it in boundary value experiment.

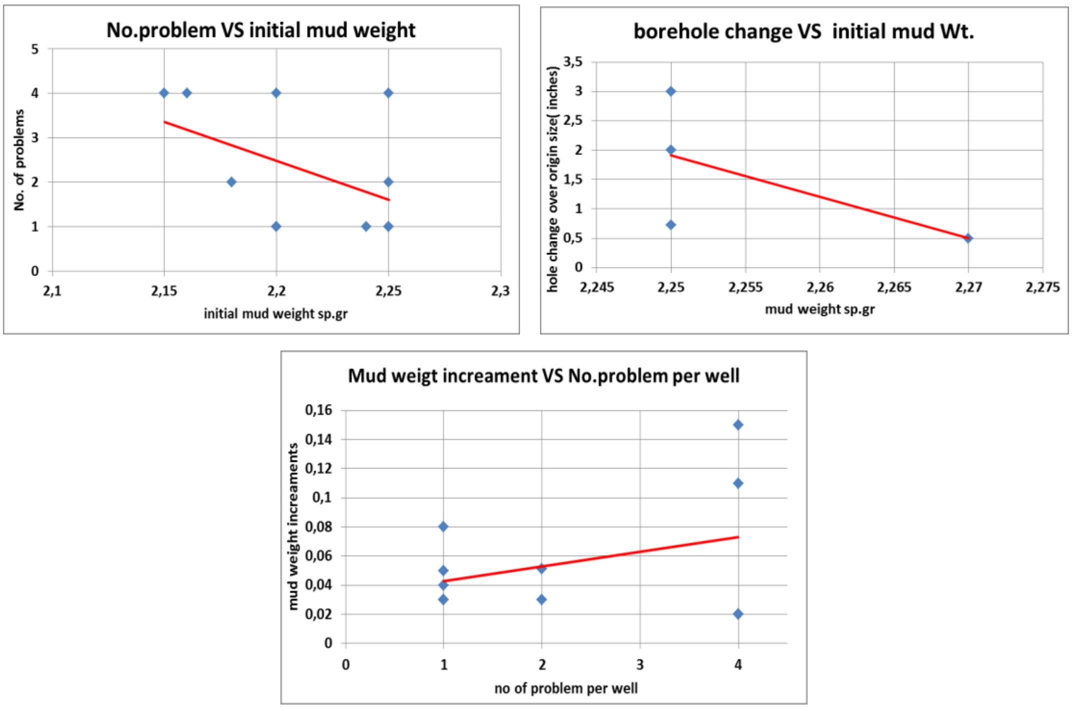


Figure 1-6 increasing mud weight effect

It should be mention here, all case studies that was happened earlier (during drilling) or later (during completion), have been got collapsing of the casing front of rock salt.

In order to get a clear picture of the simplified case study, the figure (1-7) has shown the planned drilling progress and the real. It’s so clear that the non-productive time which was consumed to solve collapse casing, it was spent approximately for one month to open the obstacle. However, the solution had given instantaneous way to overcome the problem, it can said, was intervention.

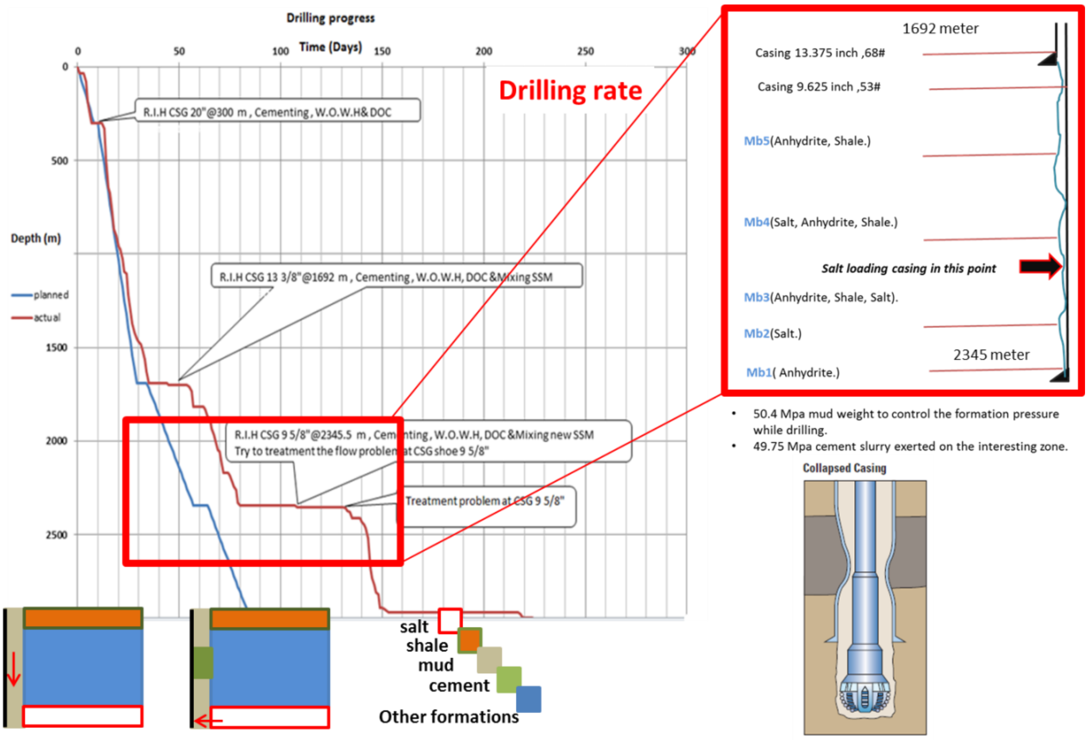


Figure 1-7 actual and plan drilling progress in Lower Fars (front rock salt)

Here, the problem is not connecting with drilling operation itself, because the rate of drilling in plan and real was the same, what does it mean? The drilling mud that was used to excavate the hole is enough to support the borehole in general, or at least trying to decrease the effect of new stress distribution that was created by excavation operation, but general view was pointed to the cementing operation which was not good enough to support the casing, then the salt rock found enough space for creeping and loaded the casing, caused by deviatoric stress which was created because absence support of the drilling mud in those closed space to inhibit this creeping. Here, the salt was loaded the casing. It has recorded the reduction inside the casing reach to (9 mm), that had been blocked the way front of drilling operations. See figure (1-8).

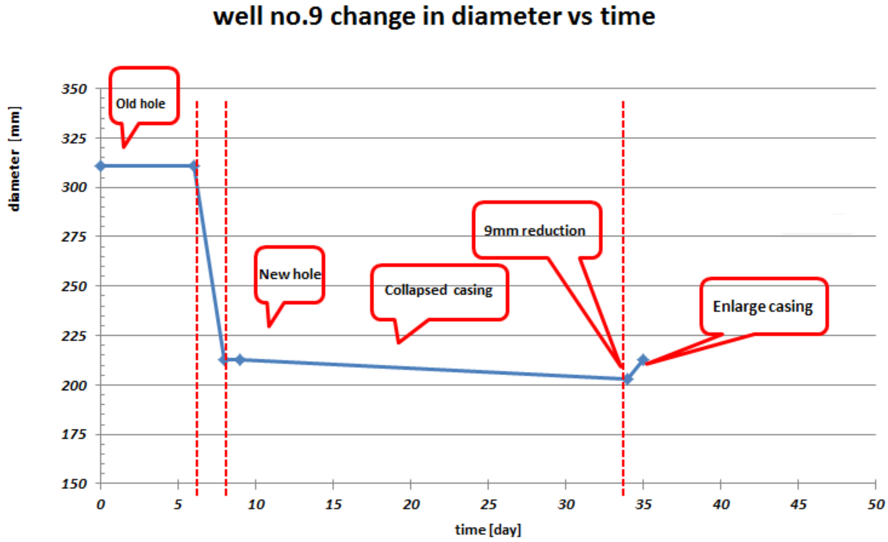


Figure 1-8 collapsing the casing of well no.9 processing

Again, the reason which mainly effected and it was the same factors which shared most other cases studies, the cementing operation. Most cementing operations that were done for all casings, was considered bad, this factor play big role in this problem, return back to the figure (1-8), approximately one month was spent, to finish this process. So what it was needed? To outline this case study as follow:

- Stress distribution.
- Temperature distribution.
- Cement evaluation front of interest zone.

1.3.1. Stress distribution

The other effecting factor on behaviour of rock salt is (stresses difference) or in situ stresses distribution, when the two horizontal stresses are not equal, the result will be elliptical shape rather than circular when it will equalise. It has been shown that in the figure (1-9).

So, the drilling mud that fills the borehole of the oil well plays a big role to mitigate this difference. Most of time, the drilling mud pressure will be equal or more than minimum horizontal stress, while the maximum horizontal stress are so high compared with minimum horizontal stress, that its meant , that some parts of the peripheral of the borehole wall will be under deviatoric stresses, resulting elliptical shape of borehole. Despite the borehole was reamed by special tool, in order to get circular borehole and decrease the stand-off the casing with the borehole but the period between reaming and setting the casing on the borehole is not short.

(Haimson et al.,2003) Haimson was created new apparatus, which can test a rock under independent three stresses. It was done experiments on cubical specimen with borehole of the Berea Sandston, in order to see the borehole damage .see figure (1-9)

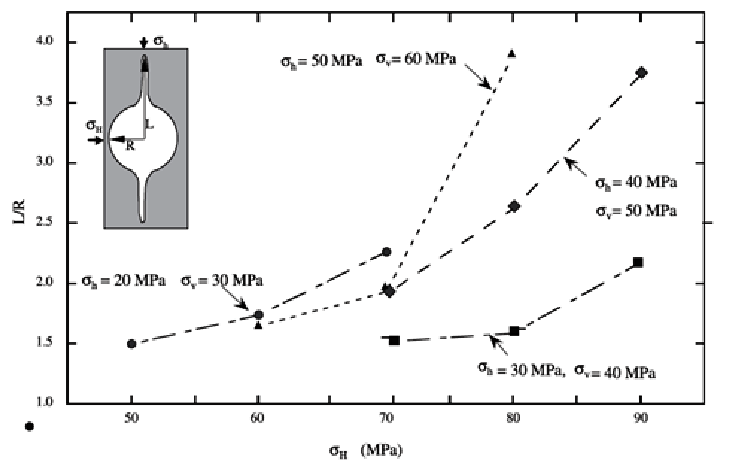


Fig. 6. Variation of normalized breakout length, L/R as a function of σ_H for the same magnitudes of σ_h and σ_v, showing a direct correlation between breakout length and far-field stress conditions.

Figure 1-9 breakout on borehole that exposed three independent (Haimson et al.,2003)

In the same context, Mohr- Coulomb shear criteria is the most failure criteria that is being used for analysis a borehole stability by getting a drilling mud weights window ,which is extended between high value (tensile effect),and low value(breakout),which neglected effecting of maximum horizontal stress when assumed the same value of minimum horizontal stress. See figure (1-10). On the other hand, later was discovered that this assumption given not realistic result in crystalline rocks (Wiprut et al.,2000).

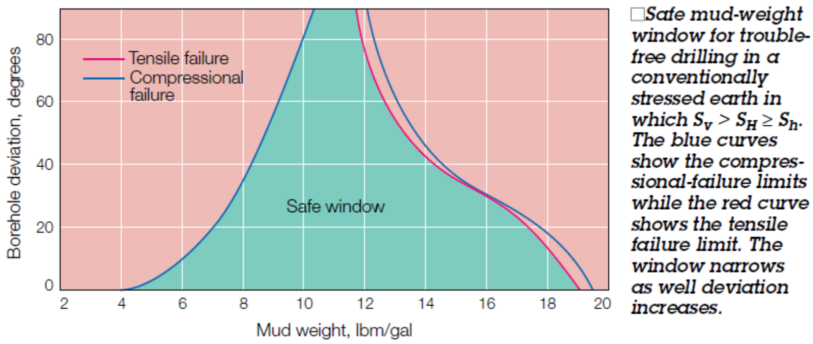


Figure 1-10 mud weight windows with borehole deviation (Addis et al.,1993)

1.3.2. Temperature effect

Rock salt is considered characterized type due to its' properties of low strength and strong rheology, this strength is affected by stress differences, temperatures and loading rate, as well other factors (humidity, grain size….).

The temperature effect on creep rate when it is increased, and then decreased compressive strength (Handin et al., 1958) (Hanson et al., 1980), as well the temperature effects on tensile strength and tensile creep deformation.(Wisetsaen et al.,2015) which was shown the rock salt is very sensitive for loading rate and temperature.

The temperatures extend between (66C-80C) for the most Iraqi cases studies, in specify front of the rock salt.

The temperature is one factor which accelerates plastic deformation in the rock salt. So, a sufficient deviatoric stress and temperature, a steady state creep will be reached. The temperature, as well deviatoric stress effects directly on rate of distortion for change in shape that depend upon material or structural parameters. See figure (1-11)

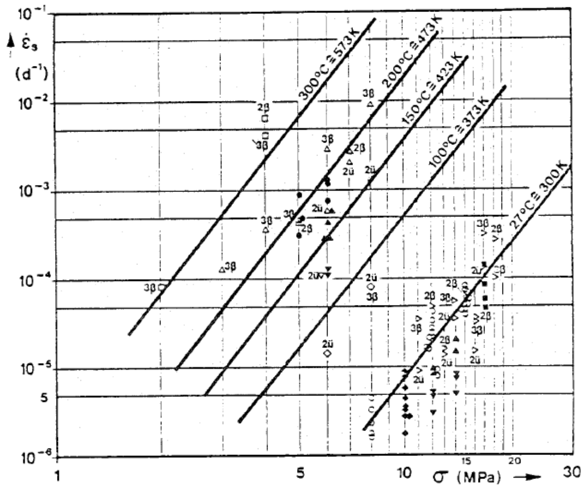


Figure 1-11 creep data of rock salt (according to tests by BGR) (M. Lange et al.,1982.)

The borehole sections that characterized instability problem for Iraqi case studies have different depths, then different temperature, as its mention. This factor has been taken as strong effecting variable for study (experimentally).

1.3.3. Cement evaluation front of interest zone.

The cement operation is other important factor effect on the borehole instability in oil well. So, for instance if we consider that the casing will cemented , then it should study considerable factors that acting directly on cementing, as tensile strength of cement sheath , which has connected directly with the pressure inside casing. This pressure affects by changing radial stresses and then the hoop stresses in cementing sheath. For instance the hoop stress will be increased in value more than the initial tensile strength of cement, see figure (1-12), which has shown increasing pressure inside casing will increase the hoop stress inside the cement sheath.

Cementing operation is affected by different factors, as: drilling fluid properties, oil well design, wellbore preparation and conditioning, operational parameters, centralization parameters, displacement efficiency parameters, cement slurry parameters and cementing equipment.

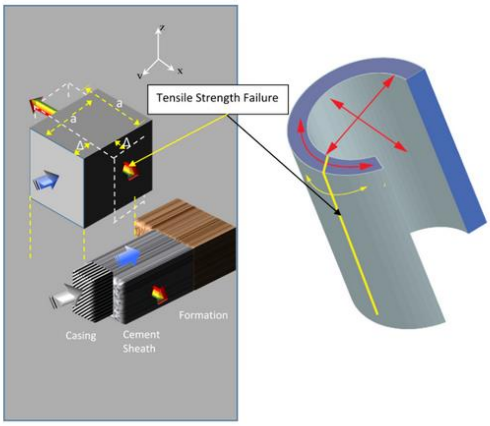


Figure 1-12 cementing sheath between casing and rock effecting by casing pipe pressure ((M.Venturino2016)(De Andrade et al, 2016)

For instance in the complexity, if the cement has some channels, and if the inner sides of the pipes casing will be exposed for decreasing or increasing in the pressure, these channels will act to amplify the stress on the cement sheath by 3-4 times, then effecting on the tensile stress of the (cementing casing/ cementing rock) sheath (A.Lavarov et al., 2016). See figure (1-13)

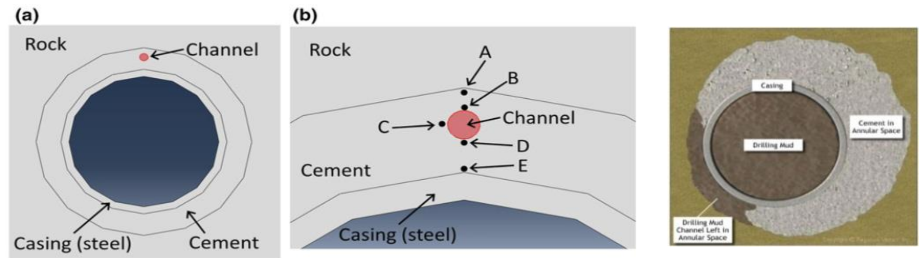


Fig. 5.7 Geometry of a cased and cemented well with a void channel *left* in cement

Figure 1-13 Geometry of a cased and cemented well with a void channel (A.Lavarov et al., 2016)

For sack of simplicity, our case study here has been assumed the casing pipes without cement, in reality this assumption was accepted because there are lot of casing pipes sections, have been left without cementing.

Perform a correct estimation of all parameters and anticipate all the events that will occur during the life of the well in not only difficult, is impossible.

Logging tools are the best way to check cement around the casing pipes, despite the big development through this part of the oil industry; the sonic data log is commonly used.

The sonic data logs (Iraqi case study) have shown bad cementing bonds near to the depth where, the casing pipes were loaded by salt. Sometimes, it can be said, there was not cement even for fewer meters especially front of rock salt, which meant leave the casing without any support by cement, and then sufficient deviatoric stresses, accompanied with temperature, however new log techniques have been shown that some parts from casing were covered by cement the other not.

All signs indicate that, the casing pipes were loaded with non- uniform way as result of the creeping of the rock salt. See Figure (1-14)

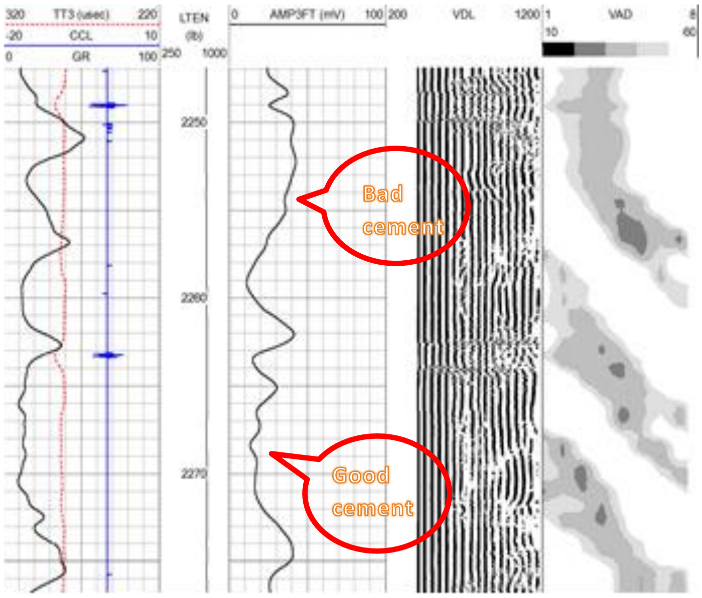


Figure 1-14 sonic log for interested area, showing a good and bad cement zones.

However, even the cement sheathe behind the casing has compressive strength but was not good enough to support the loading from the rock salt deformation, so it can assume, there is not cement sheathe behind the casing .

On other hand, from chemical point of view, it might be some question here, Does the drilling mud (salt water base) was chemically affected by dissolving some of the rock salt? The chemical history of salt saturation drilling mud through drilling these borehole sections, have been shown chemically stability generally during drilling operation, as it has shown in the figure(1-15)

So this factor will not be considered through this thesis. However, the drilling mud create wet environmental (humidity) this factor is very important also, which support creep processing, farther more, the complexity of Iraqi rock salt because it is considered as secondary rock salt.

The Iraqi rock salt has lots impurities as clay and shale, and then the wettability for these materials differs from origin rock salt, which needs special study.

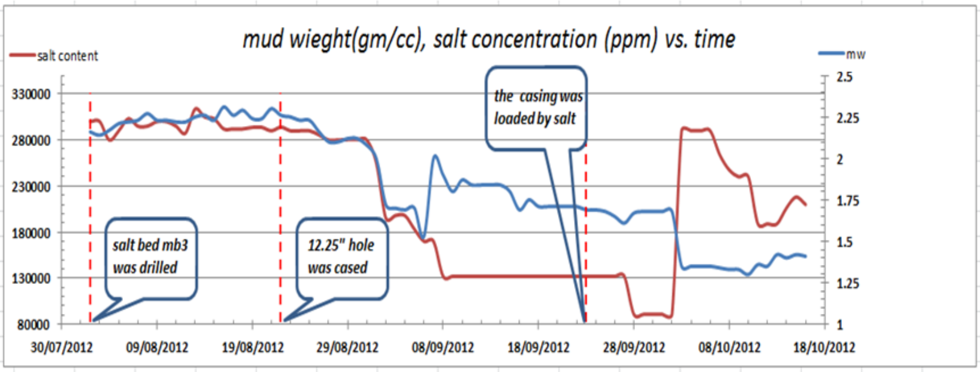


Figure 1-15 salt content of drilling mud and mud weight vs period of drilled, cased of rock salt.

1.4. Definition of the problem

1.4.1. Selection simplified assumptions

In order to look for the generalization of the case study, which had been occurred, it should be simplified and focusing the work in order to get the good analysing and predication by using the best bench scale experiment .and good constitutive models, so it can be assumed:

- No cement sheath
- No pressure behind the casing which decrease the salt loading.
- No chemical effect.
- Ideal casing (non- wear casing).
- Casing centered on a hole.

The worst scenario for all case studies, which consist from the assumptions above, which was considered reasonable and make the target clear and generalized one case study with that worst scenario, see figure (1-16).

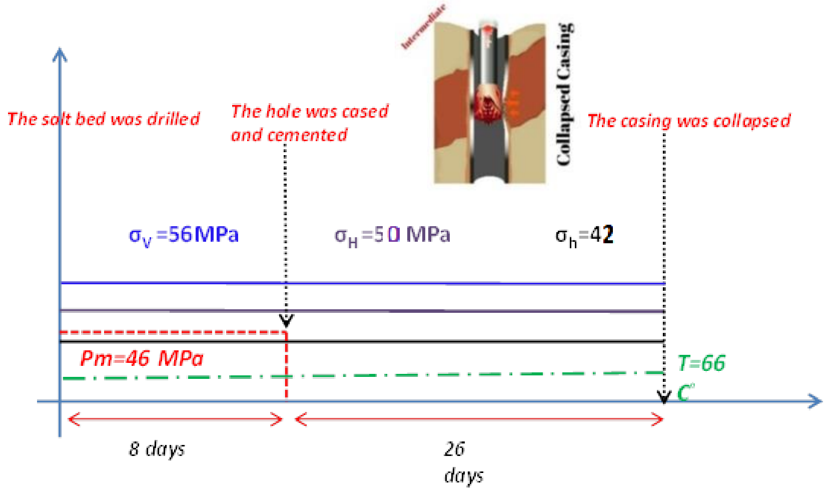


Figure 1-16 stresses distribution of rock salt case study

The Iraqi rock salt is under three different in situ stresses (vertical about 56 MPa) maximum horizontal (50MPa), and minimum horizontal (42 MPa). The equilibrium had not changed too much by excavation process during the first period, till the casing was set, because the wall of the borehole was supported by the mud pressure which, approximately equal to minimum horizontal stress. On the other hand, the rock salt would be under sufficient deviatoric stresses. These stresses difference had initiated, when un-cemented casing pipes were set at the planned depth and the wall of the borehole was loosed the drilling mud supporting because the bad cementing operations.

It was happened at the end of the first period (8 days).

So, the sufficient deviatoric stresses, as well the temperature which accelerated the deformation , which it has shown in figure (1-16), after (26 days) from this deviatoric stresses with temperature, the casing was loaded by salt, which was led to stop the drilling operations, due to the restriction inside the casing pipe due to collapsing.

1.4.2. Suggestions applying mathematical models of non-uniform loading

Collapsing casing pipe is a famous phenomenon in the oil industry, as it was mentioned, due to external load on tubes which have shown different results in oil well. Despite the casing was designed to resistance external load that depends on mechanical and geometrical parameters. There are two methods that are used to define and evaluate collapse resistance in casing design.

1.4.2.1 American Petroleum Institute (API) Collapse formula (API 5CT)

Under this item there are 4^{th} formulas which were defined by API that classified the collapse region into 4^{th} domains, depending on (D/t) ratio and grad of casing pipes as follow:

- Yield strength collapse.
- Plastic collapse.
- Transition collapse.
- Elastic collapse.

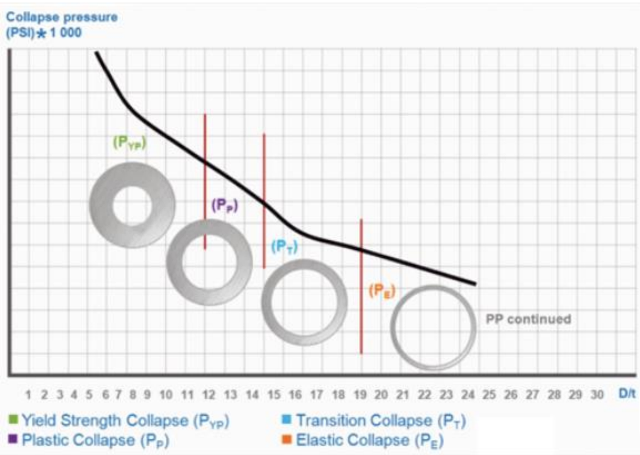
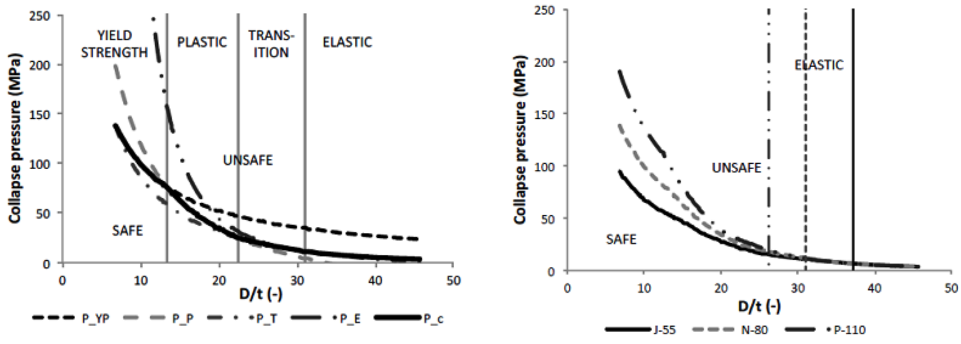


Figure 1-17 Domains of collapse casing region by API 5CT (Vallourec)

The figure (1-17) has shown clearly these domains. The Yield strength collapse domain ,the main parameter control is mechanical parameter, which depend mostly on the material yield strength. This concerns the low (D/t) ratio (outside diameter or thickness of pipe).

On the other hands, the elastic collapse depends mainly on casing pipe geometry, and not on yield strength of material (large outside diameter of casing pipe).

The results was get by using this method, is conservative, for example how to use these domains the figure (1-18) has shown the safe and unsafe regions of different domains with different grades of casing.



: Grade N-80 collapse pressures (left) and grade J-55 vs. N-80 vs. P-110 collapses pressure (right)

Figure 1-18 fourth collapse pressure zones vs D/t (11)

1.4.2.2 Statistical approaches based on collapse tests (API 5C3)

Two annexes (G),(H) of ISO10400/API 5C3 that describe collapse failure of casing pipes depend on large number of collapse tests from sample in production , for wide range of sizes and grads per manufacturing plant.

Other annex depends on empirical calculation of database from different pipes manufactures (Klever-Tamano equation).

In the same context, fields collapse data was presented for different oil well fields in worldwide figure (1-19). This figure has presented the failure casing in different fields and locations.

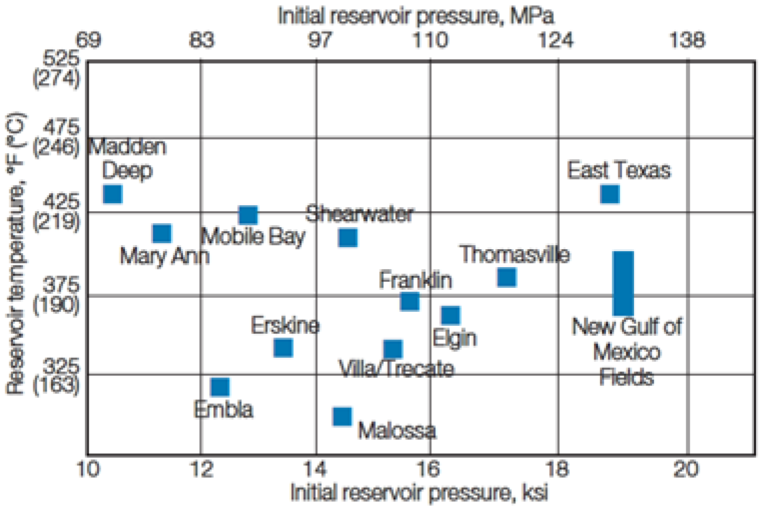


Figure 1-19 fields' collapse data of HPHT (Staelens et al., 2012)

The (D/t) for Iraqi case studies of casing collapse ranged between (17.23-20.39), which is meaning all cases studies between two domains(transition collapse and elastic collapse).

So, the problem is connected by both geometric and yield strength material for most of Iraqi cases studies.

1.4.3. Analysis of Iraqi case study by applying two theoretical models

From mechanical point of view, two theoretical models have used based on theory of curved beam to analysis the stresses that are initiated by non-uniform salt loading. One of them was applied for USA field's data, and the results were realistic, while the other was checked by experiment tests that were done on casing. All calculations have followed to the two mentioned methods of selected models (Hackney et al., 1985),(Lin et al., 2014).

These models were choose because the non-uniform loading ,small restricted area from the casing would be under the rock salt loading , as was mentioned before , most researches has been said that the non- uniform loading of the casing will reduce the resistance of collapse casing by (15-30)% of uniform loading. Farther more, elastic and elasto-plastic numerical models were applied to check the two analytical solutions. See the figure (1-20)

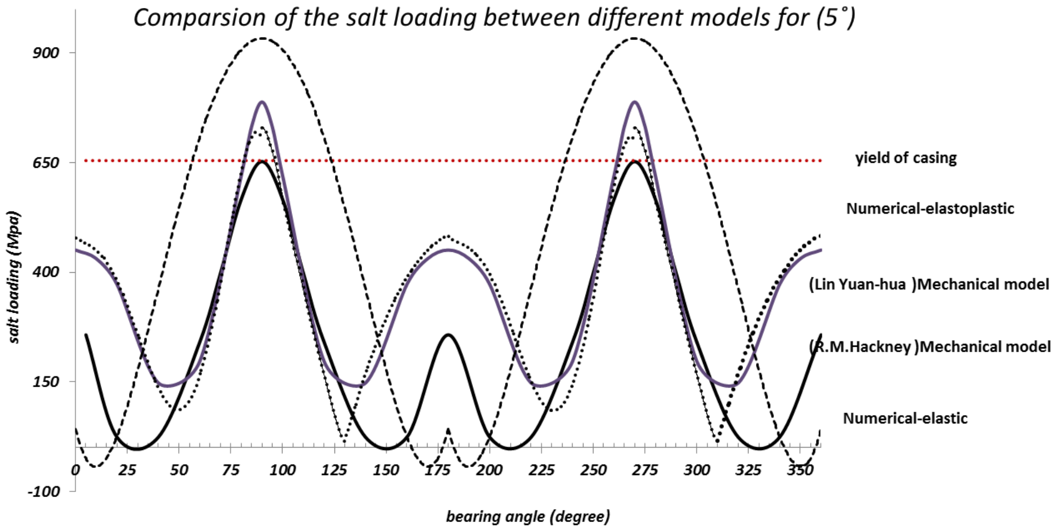


Figure 1-20 analytical –numerical solutions for Iraqi case study

The figure has shown both models predict the casing collapse when the boundary conditions, as assumed (bearing angle 5˚, no cement behind casing, non-wear of casing).The both collapsed point was opposite each other.

The elastic numerical solution has given overestimate predication, while elasto-plastic numerical solution predicates value between two analytical solutions. Generally all solutions, analytically and numerically have been shown failure the casing through Iraqi case study under non-uniform salt loading.

1.4.4. Focusing the target of thesis

The target of this these to analysis case study from geo-mechanical point of view, by re-producing the case study in laboratory scale (boundary value problem).This aim need different steps, as follow:

- Find solution for the few quantity of rock salt raw material.
- Study mechanical properties of rock salt (standard, advanced) by experiments work.
- Elementary borehole closure creep test.
- Study the stress path of boundary value problem test.
- Numerical solution of constitutive models for boundary value problem test.

1.4.4.1 Facing the low amount of material extracted from deep borehole of the Iraqi rock salt formation.

The cost to extract rock salt from underground depth reach to (2600 meter), is the controlled key for quantity of study material. The amount of Iraqi salt that was designated for this thesis is so few (cylinder core with dimension 100mm X 600 mm), as well it is irregular shape, and was separated into five pieces. See figure (1-21).

Figure 1-21 Iraqi rock salt in the oil field

This material is not enough for the target of this thesis, so the solution was put to find another material that has the same geological age (Miocene). The Italian rock salt (Petralia) is good alternative solution for this problem; however the difference between them by structural is very clear.

1.4.4.2 Features of the geomechanical investigations for both Iraqi and Italian rock salt

It should put an experimental matrix in order to organize all laboratory equipment's for this task. The work would divide into two stages:

- Standard test
- Advanced tests

Both tests are important, because the elastic static properties will be extracted, that are needed for most constitutive models. The creep tests are more important because, are considered the main reason for loading the casing.

The advanced test needs some improvement for measuring devices. These devices are the base for this type of experiments (multistage tri-axial test, constant mean stress….etc.).

1.4.4.3 Definition of the elementary borehole closure test

This step is considered very important to detect, what are needed for a experiment that related to a thick wall hollow cylinder sample, which is considered part from re-produced case study, as well, elementary long term creep test for standard sample and hollow cylinder and what are instruments that should developed.

Different size specimens were put under different types of tests, as, uniaxial compression creep test, uniaxial tensile creep test, and uniaxial compression creep test for hollow cylinder specimen.

Development prototype measuring device for borehole closure, and test it under elementary creep test, in order to get way for advanced tests.

1.4.4.4 Definition of the stress path of in the borehole closure test

Re-producing the case study in laboratory scale needs to create apparatus which can mimic the boundary condition on a specimen of rock salt. It should start from the available laboratory equipment's.

Hollow cylinder tri-axial test, is the best choice to reproduce the Iraqi case study because this test gives clear view what will happened in borehole closure under different boundary conditions. This test needs a lot, to develop and improve the available equipment's.

The plan demands to think and build new apparatus that help us to study and measure the borehole closure in the rock salt under boundary conditions (high pressure , temperature), as well to overcome difficulties, that connect with measuring deformation tools .

The hollow cylinder equipment's' , are still being improved by researchers to get the simplest and more accurate to measure the deformation inside and outside rock specimens under independent stresses.

Among apparatus which was created to study geo-structural problems, for instance, one of these apparatus which was designed (R.T.Ewy et al., 1990) base on plane strain, as well gives the ability to control the internal and external pressure independently, beside it used molten woods metal, which injected inside the apparatus to take the shape of borehole damage. See figure (1-22).

Farther more, the good point through this apparatus; it can move the external pressure from finite to infinite by using outside steel jacket which has stiffness close to the boundary rock value.

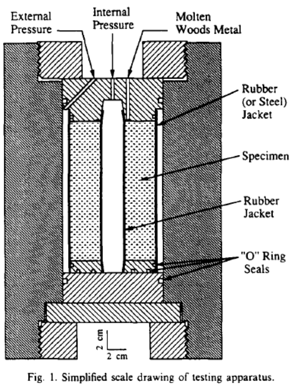


Figure 1-22 sketch for borehole closure apparatus (R.T.Ewy et al.,1990)

So, there are two options to simulate the case studies, the first by using tri-axial equipment's; after modification, and secondly by design new apparatus, which it can measure deformation inside borehole of rock salt after applying external pressure under plane strain base. See figure (1-23).

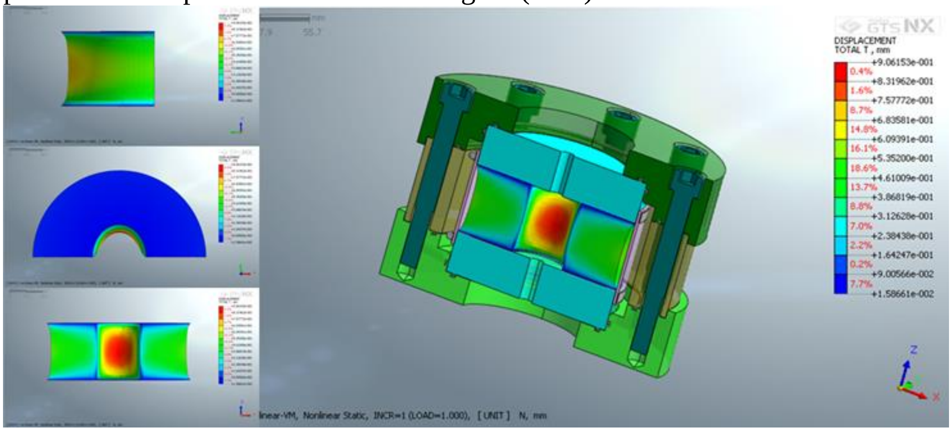


Figure 1-23 first design borehole windows apparatus

The key points for designed and build this apparatus are to evaluate case studies and to apply stress paths of their boundary condition.

Now it can introduce the stress paths for the problem that should apply it on rock salt to discover a load on the casing pipes, which easily represented by three outlines of the stress paths. , as it can see through figure (1-24)

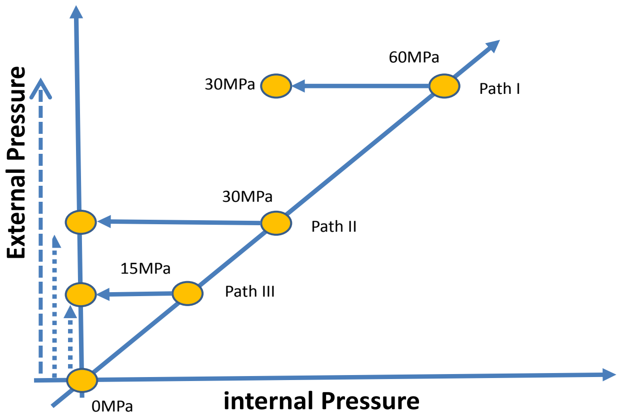


Figure 1-24 stress path for boundary problem test.

The outlines of “the boundary value problem" experiments should be followed the stresses paths. The numerical solutions were used here, to test all stresses paths that can give the ability to select the suitable apparatus from geomechanical point of view as well practical.

Most stresses paths have applied for hollow cylinder rock salt specimen ,which have dimensions (100 diameter. 100 mm length, 38 mm borehole) ; however, this dimensions of the specimen are convene with Italian rock salt properties , but not with the Iraqi rock salt because grains size.

Two ways have been applied to get the planned paths, direct way which, the specimen does not pass into the hydrostatic part from the test, just the devaitoric part (doted arrows in figure (1-24)). This has represented by (Borehole windows apparatus with PIV technique).

The second way, the specimen has passed into the two parts of the test (Hydrostatic, devaitroic),(stress path I, II, III),the modified triaxial cell is the apparatus which can do that.(solid arrows in the figure(1-24))

.

1.4.4.5 Preliminary numerical analyses to validate the borehole closure test concept.

The numerical code (GTS NX) was used, by check all the stresses paths, using elastic and elastoplastic by take a quarter 2D plane strain of the rock salt. See figure (1-25).

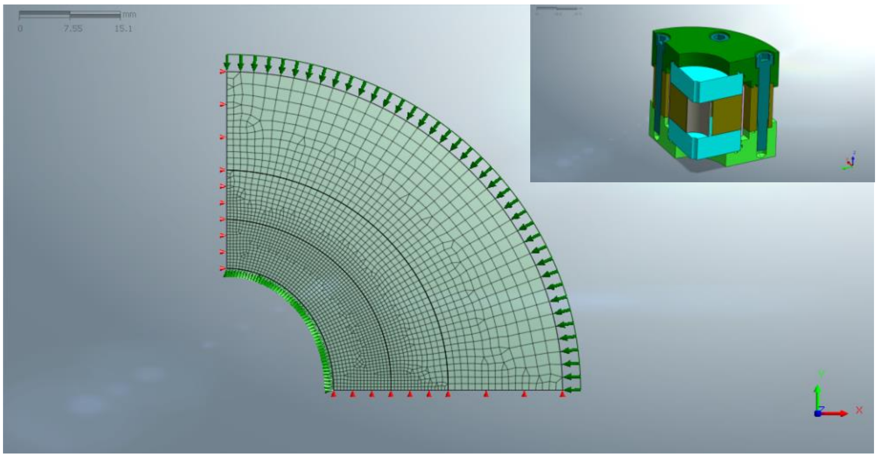


Figure 1-25 a quarter of rock salt under boundary condition

It has seen, when applied hydrostatic condition (60 MPa), then apply deviatoric stress (30MPa), (stress path I) the effective strain are not difference too much when it has followed stress path (III) , that was done by applied hydrostatic (60 MPa), then reduce it to (15MPa), later apply deviatoric stress (15MPa),the reason behind that, the confining pressure which play big role in rock salt, because for stress path (I) even though, the deviatoric stress is (30 Mpa) but the confining stress also (30 Mpa), which force the rock salt to be under dilatancy boundary, so the effective strain is close from the stress path when less devaitoric stress(15Mpa) without any confining pressure, stress bath (III)

However, the big difference has been occurred when follow stress path (II), when the rock salt specimen was under hydrostatic condition for (60MPa), then reduce this hydrostatic to (30MPa), and finally apply devaitoric stress (30MPa). Here the effect of deviatoric stress (30Mpa) is very clear when the confining pressure zero because ,the compressive strength of Italian rock salt is (29 Mpa) such that the rock salt has already entered in damaged area near to failure See the figure (1-26).

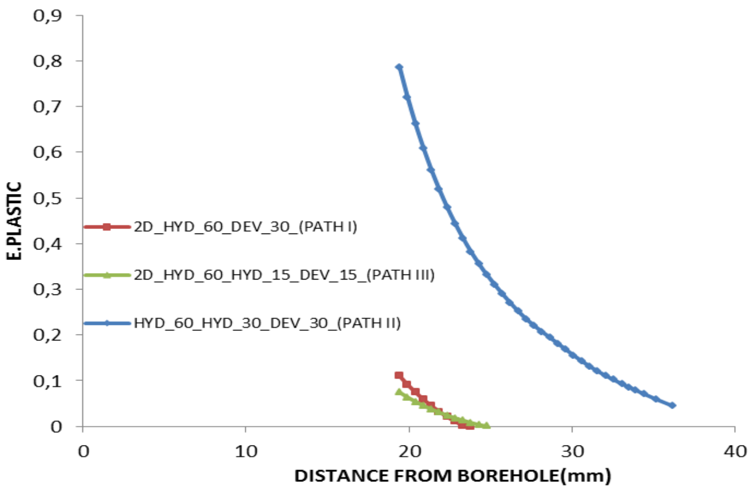


Figure 1-26 effective strain vs. distance from borehole for different stress paths

It seem that when the deferential stress is low ,of course the effective strain will be low, and when it will increase to double for stress path (II).the effective will be more of course, as well, through this path , the stress history has been effected, because the hydrostatic stress supported healing processing .

On the other hand, the coincide between stress (I) and (III) because here there are two factors play, one of them in the stress path (III), the differential stress are low, and the other factor, in stress path (I) the confining pressure has been effected.

Farther more, the stress path that represents by dashed line, the rock salt has been under just differential stress, (borehole windows apparatus or hollow cylinder test), the numerical results has been shown some convergence ,when the rock salt has been passed in hydrostatic or go direct .See figure(1-27)

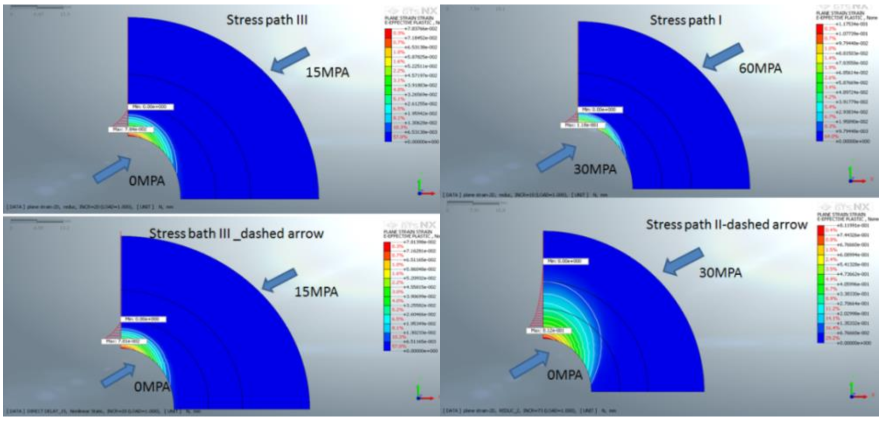


Figure 1-27 effective strain for different stress paths

The figure has shown two points, 1st the effect of hydrostatic test before apply the deviatroic stresses, which it has shown clearly in this figure. 2nd the effect of confining pressure on the deformation of rock salt.

the effect of confining pressure on inelastic deformation,is clear on strain stress curves, for unconfined compression are about 30% lower than those obtained at confining pressure of 20 MPa., and it's clear this effect in the numerical solution above.

Briefly, the two appartus ,can be suitable for representive the "boundary value problem " experiments', but the priority is for the modified tri-axial apparatus ,that is used hollow cylinder specimen, because it give more options to apply different stresses paths , which is meant, it can apply hydrostatic stresse , as well giving wide ranges to apply devaitoric stresses under different confining pressure .While the "borehole window apparatus" was designed, to work in the plane strain, and work under just devaitoric stress without confining pressure .

Chapter 2: Overview of well bore stability and rock salt behaviour

2.1. A general review

The drilling operations for oil and gas exploration and production under different geological environments nowadays need to understand rock geomechanics, in order to get safe borehole and effective drilling without problems, which meaning less NPT (non-production time) , therefore an efficient drilling without problems (instability of borehole) should be the target .The good assessment to the most important boundary conditions and mechanism will lead to overcome the borehole instability, according to these bases , the success to plan, that depend on the best estimation of the drilling muds weights and the geo-mechanical well layout. Drilling of deep borehole through wide range of pressure gradients in different type of formations, face more difficulties due to differences in the variations of local stress field near to the wellbore of every formation.

This may have negative impact on the well construction (see Fig. 2.1) The possible borehole issue which is created by this variation in local stress can be as below:

- Failure of borehole wall due to breakouts.
- Swelling shale or creep of evaporates (as rock salt) into the well.
- Activation of exist joints or fractures resulting fluid losses.
- Some developed borehole stability lead to kicks.
- Compaction of porous rocks resulting in reduction of reservoir porosity/permeability. (L.Ma et al., 2013)

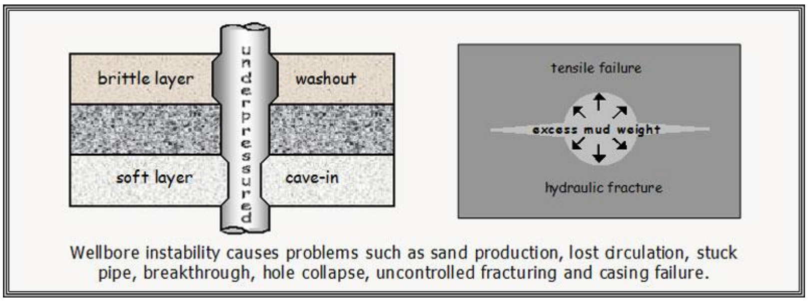


Figure 2-1 two type of borehole stability (S.Peng et al., 2007)

The drilling of borehole generally is looked for creating dimensionally stable calendric excavation in which the casing pipes can be installed .The most operation situation that put the drilling progress at risk due to instability of the borehole, is fluid losses, which create hydraulic connection, later negative impact for the well.

Drilling into the earth crust and replacing the heavier rock materials with a lighter drilling fluid cause stress concentration around the wellbore. The degree of stress concentration depends on the wellbore orientation, the magnitude and orientation of in- situ stresses (far field stresses), and the wellbore pressure (Bradely et al., 1979).

In order to control borehole stability, it should have all data that connect with in situ state of stresses and geo-mechanical properties of penetrated rocks, those two factors should determine exactly, as possible, as well as, a good geological models which consist of, the thicknesses of formations, faults, and natural fractures, are considered the base step to create good geo-mechanical layout which enrich the data, accompanied with the drilling mud properties.

Precise data of the in situ stresses refer to robust and comprehensive geo-mechanical model, as usual, failure will occur when the resulting stresses around the new borehole are larger than rock strength, and might be will activate the exist fractures when this new value of stress overcome the frictional strength, furthermore some rocks have some fluid inside their porosity which effect on value of these stresses.

The vertical principle stress can be estimated from the thickness of uploaded formation, and their densities. However , the other two horizontal stresses, can obtain from leak of test, within drilling operations .These stresses ,will be redistribution around borehole, that can lead to change the local stresses along the borehole wall.(see Figure. 2.2) the easiest way to describe it, is to use the analytically stresses variations (Kirsch- equation).

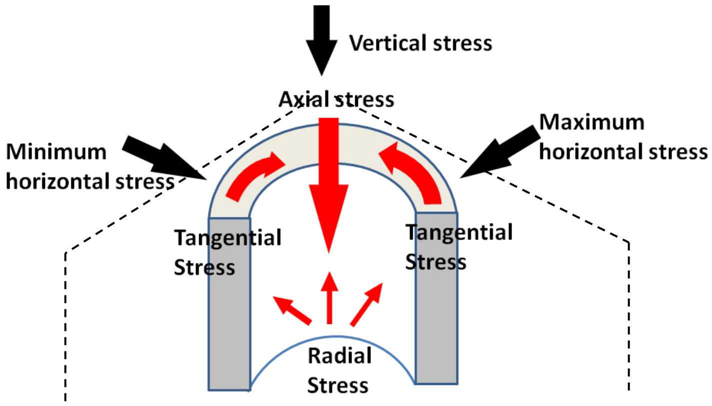


Figure 2-2 Alteration of the local stress field close to the wellbore (Pasic et al.,2007)

The main important parameters that can be controlled are mud weight and, mud temperature, which is used to substitute the disturbance in the in-situ stresses (far field stresses) depending on mechanical rock properties. The high value of hoop or tangential stress leads to failure of rock. High mud weight leads to reduce the effect of local stresses(tangential stress), on the other hand may be will lead to worst case, where the borehole has slip of high angle joints, or may be also cause induce fractures by tensile effect.

Drilling induced tensile fracture (DITF) ,develop when the local tensile stresses exceed the tensile strength of rock, this type of failure generally occurs in direction of maximum horizontal stress, while if the drilling mud weight is more than normal, meaning its higher than minimum horizontal stress, this situation will be far to create DITF but it will be very close from mud loss which will be happened by fractures which may be activated or induced ,then low head of mud level inside the well, which leads to more instability problems., actually three types of mud losses which can be faced during drilling operation partial , complete and severe losses, there are lot of reasons which lead for this issue but one of them , when the density of drilling is much high, which will lead to decrease the normal stresses that help to split some part of wall of the boreholes

On the other hand, if the local stress will be compressive, which overcome or exceed on the compressive strength of the rock, the breakouts as a result, the larger stresses, and the larger break out angle, which lead to caving in the breakouts zones. For instance if the certain breakout width is more than 90 degree, the borehole collapse, predicate significant caving and may be stuck the drill string.

Rocks generally show deformation, when acted stresses is changed, some of that change will be small; it is considered elastic deformation, which can be described by Hoek's Law.

Larger changes may be lead to brittle failure of rock as (sandstone, limestone and granite) ,and other will have macroscopic rupture, but also with ductile behaviour due to time –dependent deformation, which is called creeping as ,in the salt and shale.

These type of rocks when will face in drilling operation, can show reduction on borehole diameter, and most of times such borehole sections need to be re-drilled. The drilling induce rock deformation, which can lead to oval shape in the borehole (two horizontal stresses are not equal) or spallation of the borehole wall; both of them effect on the drill progress or even loss of the borehole.

The ductile deformation depends on the magnitude of change in stress below a critical value for damage (dilatancy boundary), and its time dependent. If a critical stress (rock strength) is reached, fractures are initiated that coalesce. A Failure occurs when the fractures connect to a free surface. See Figure. (2-3)

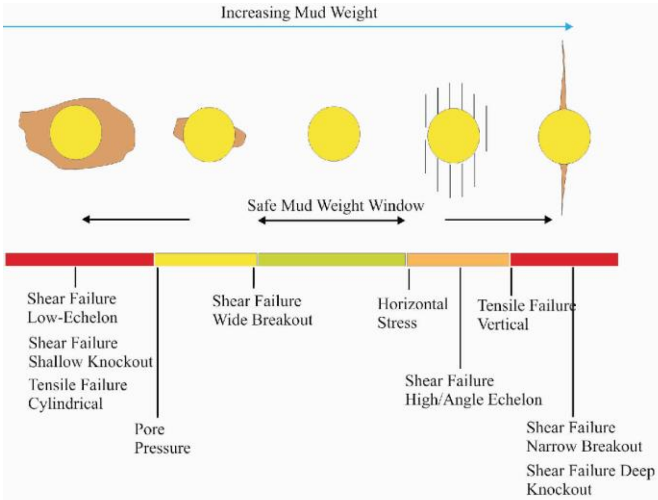


Figure 2-3 Changing borehole shape with different forces (Pasic et al.,2007)

The figure has been summarized all types of failures for both, when increasing mud weight or decreasing mud weight below the pore pressure .For these two general cases, there are failures at tensile and shear ,but the patterns of these failures are different. When the mud weight are too much lower than pore pressure, there are two types of failures, the shear failure will be low-echelon or shallow knockout, while the tensile failure is cylindrical. Farther more, there is another shear failure region, after overcome the pore pressure in a small amount, which is called “shear failure wide breakout”. Now, it can be discovered a safe window to drill a borehole without any problem till reaching to value of maximum horizontal stress. If the drilling mud weight exceed this value, a new region of failure will appear, which characterised by high angle echelon. In addition, the Farther increasing, in the mud weight, the failure will be in tensile failure region, but in the vertical pattern, more increasing in the mud weight, this failure convert to shear, that characterized by narrow breakout.

In brief, the tensile failure can be done by three patterns:

- Cylindrical when radial stress lower or equal tensile strength.
- Horizontal when axial stress lower or equal tensile strength.
- Vertical when tangent stress lower or equal tensile strength.

While the shear can be summarized as follow:

- Shear failure shallow knockout, this failure will be in plane of radial/axial because ($\sigma_a>\sigma_t>\sigma_r$).
- Shear failure wide breakout, this failure will be in plane radial /tangent because ($\sigma_t>\sigma_a>\sigma_r$).
- Shear failure high angle echelon, this failure will be occurred in the axial/tangential arc because ($\sigma_a>\sigma_r>\sigma_t$).
- Shear failure narrow breakout, this failure will be occurred in the radial/tangential plane because ($\sigma_r>\sigma_a>\sigma_t$).
- Shear failure deep knockout, this failure will be in radial/ axial plane because ($\sigma_r>\sigma_t>\sigma_a$).
- Shear failure low angle echelon, this failure will be in tangential /axial plane because ($\sigma_t>\sigma_r>\sigma_a$).

Some borehole stability problems, is connected with pre-existing faults or fractures; those can be activated by the changing of the stress state, especially when it use the high drilling muds weights which can propagate of the existing fractures, which may lead to more caves in the borehole, generally , this case can take a name “slip tendency analysis”(Moeck et al.,2011), If the drilling operations use the high muds weights in a high natural fracture formations, the filtration of the muds will penetrate through fractures, then some rock blocks will slip , later the borehole shape will be intensively oval shape. The oval shape is supported by some activities during drilling operation which creating an imbalance in the pressure of the bottom borehole, as result swabbing(by pulling faster drill string) and surge pressures (by running faster drill string)assisting the fracturing of rock or cutting to be split(Ping et al 2007). Sometime the drilled borehole penetrates a fault, and might be the drilling mud invades the discontinuity plane. The caves produced by the chipping of broken materials into the wellbore can cause drilling problems, such as pack-off, over-pulls, stuck-pipe and poor cement.

The borehole pattern, affects directly on the running of tools which is used in drilling operation, if the well bore will be oval (elongation from both sides, one the other hand reduction in diameter of other side) effects on the casing pipes, and then cementing operations, for instance in the Cusiana field in Colombia, even though some measures to prevent borehole instability were taken, extensive breakouts in fissile and naturally fractured shale – of up to 44"(1117.6 mm) in 12.25"(311.15 mm) borehole was occurred (Willison et al.,1999).

Approximately 10% of the well costs in the Cusiana field were spent coping with bad boreholes; mainly because of abnormally high tectonic stresses induced by an active thrust-faulting region (Addis et al.,1993).The effect of geo-mechanic prediction is very important in any drilling plan, because it help effectively to cut the cost.

The progress drilling plan has shown .See Figure. (2.4) . the figure has shown, how the borehole instability problem effects to deviate the actual drilling trend from its' planned , especially in the borehole size 13.375 in, because the lost circulation of the drilling mud, stuck pipes and then side tracking new borehole .

On the other hand, the figure has shown the coincided trends of geo-mechanic and planned, which is meant, the source of the problem is geo-mechanical. The example was submitted by GMI (Geo-mechanics international, Inc.) under British Petroleum Company.it was spend $ 6.7 million until back to the depth that stopped.

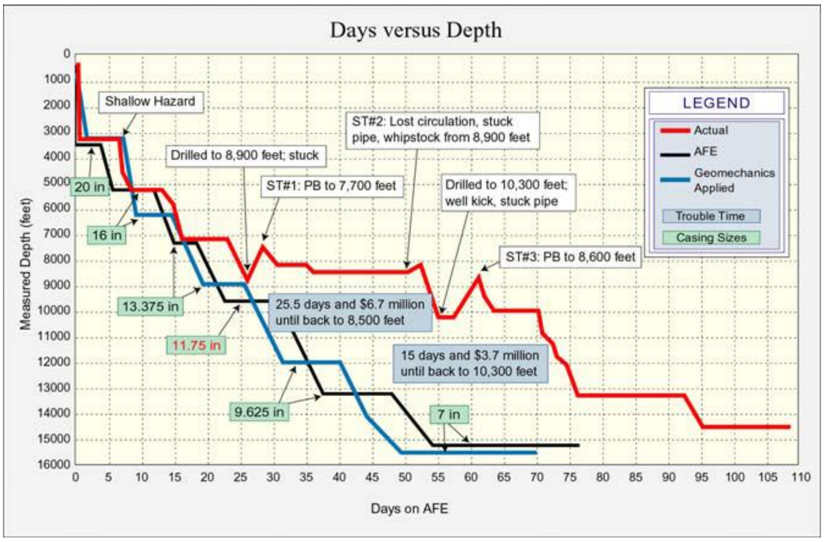


Figure 2-4 Progresses drilling operation plan and actual (wellbore stability by Chris Ward under GMI, bp (Geo-mechanics international, Inc, British Petroleum Company).

In order to prevent the wellbore instabilities and related problems', the higher mud weights are exerted pressure to support the wellbore wall. Typically, the required mud weight, is determined by a wellbore stability analysis in which the rock material ,is assumed to be homogeneous, and isotropic in mechanical properties and strength behaviour (W.B.Bradely et al.,1979), (Liu et al,.2007), (Abass et al.,2011), (Cook et al.,2007), (M.B.Dusseault et al., 2007.)

This traditionally analysis, may lead to much errors because, drilling operation face different types of rocks, and ignore the strength anisotropy associated with planes of weakness such as bedding planes will increase these errors.

This anisotropic strength behaviour as well isotropic of various rock types has been investigated by many researches (Paraschiv-Munteanu et al., 2001), (Kouprisntchik et al., 2005), (Hawkes et al., 2005),(Tien et al., 2006).

They have shown that the failure strength varies as a function of the angle between the weakness plane and the axis of the major principles stress; attaining its maximum either at (#0) or (#90), and minimum when value is between (#20) and (#40).

2.1.1. Causes of wellbore instability

Wellbore instability is caused by a number of factors which were classified as being either man-made or natural factors.

1. Man-made factors, also consist of (drill string vibrations, borehole inclination, and wash out).
2. Natural factors which consist of (high pore pressure, temperature, weak rock, bedding plane, fractured zones, and plastic rocks).

The main two reasons behind borehole instability which was classified (above) are mechanically and chemically. These two parts have shown different boreholes instability patterns.

- Mechanical patterns are included breakout, closely spaced natural fractures and weak planes, drilling induced fractures and plastic behaviour of some rocks.
- Chemical patterns which cover all above that chemically activated.

it was mention before the effect of drilling muds, so it can be put under" man - made" reasons, because the external controlling, as well, borehole inclination, azimuth, type of the drilling muds,

The other type of borehole instability can be put under natural items, which are directly connected to the condition of the formations. The natural fractures, bedding planes are considered the reason behind large caves and enlargements for existing fractures, which generally leads to borehole enlargement. See figure (2-5). The figure has shown, the maximum slip failure does not continue parallel to the σ3 direction, but with an angle of (ψ) to σ3, σ2.

The red area represents the failures caused by slip failure in the weak planes, while the blue area shows a schematic failure zone caused by both slip failure in the weak planes and shear failure in the rock (Lang et al., 2011), and time.

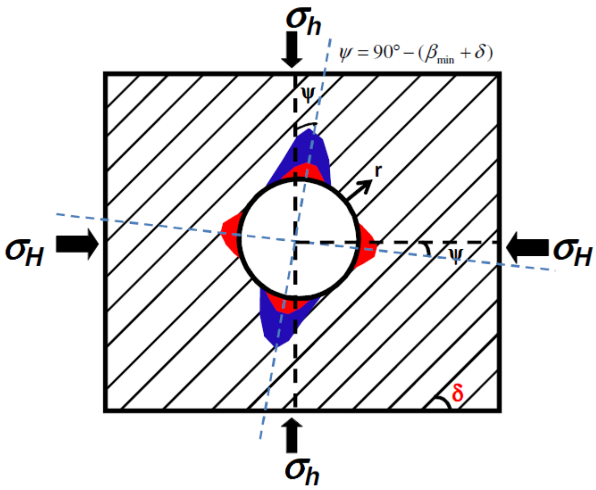


Figure 2-5 wellbore shear failures and slips failures caused by weak planes for wellbore penetrating in weak planes.

At the same context, the low rock strength cause by drilling operations, resulting to create “induced fracture” which, leads to more voids; however this result was classified under man-made.

The other important reason behind borehole instability problem is the chemical. Three factors contribute on it, mineralogy of the drilled formations, temperature and drilling muds types. The enlargements of boreholes are the results of these factors. So it can be considered that both man-made and natural classified items effect on chemical part. The temperature affected directly on dissolved processing, when water based drilling muds contact to the rock salt bed. For instance, It was created model which can connect drilling mud density, temperature and chloride content by non-linear relation that help to avoid excessive borehole closure rates during drilling (Hou et al., 2011).

In brief, its’ very clear how much the complexity of borehole instability, because those two factors play together in one state.

The good example of natural fracture is shale strength and deformability, which is widely affected by high pore pressure; the results are collapse and convergence of borehole caused by plastic formations as rock salt or marl, which have deeply affected by the borehole pressures, temperature, mud type and time. The temperature difference between drilling muds and the formations will result in heat transfer between them, the drilling mud are prepared on the surface and sometimes will be in winter months.

Through preparing brine, the concentration of salt is approximately 320 [gm./l] to 350[gm./l] but when it is pumped down into the borehole ,the high underground temperature give more dissolving capacity ,so the drilling mud try to dissolve the rock salt, making enlargement in hole.

2.1.2. Effect of in situ stresses.on borehole stability

Again, Borehole instability is dominated by the in situ stress system. When a well is drilled, the surrounding rock formations of the wellbore take the load that was previously supported from the removed rock. In another word, it is new state of stresses effect on the rock; the in situ stresses are highly modified around the wellbore. It is indicated by an increase in stress concentration around the borehole wall leading to rock failure depending on the existing rock strength.

Most of times the surrounded rocks are weak that do not support the new state of the stresses, in order to avoid borehole failure, the drilling plan must adjust the stress concentration by altering the mud pressure and the orientation of the wellbore with respect to the in situ stresses. Mechanical wellbore instability is described in terms of critical wellbore pressures that are related to rock stresses around a wellbore.

For vertical well the local effective radial and tangential stresses, are trigonometric function for the maximums and minimum horizontal stresses, pore pressure, density of the drilling mud and may be thermally induced stresses due to the difference in temperature between the drilling mud itself and rock.

The orientations of local stresses around borehole play a big role to the resulting compression or tensile. Thus, a triaxial stress field results for borehole wall is

$$[S] = [\sigma_\theta, \sigma_r, \sigma_z]^T \ldots..(2\text{-}1)$$

The three principal components:

- A radial stress component that acts along the radius of the wellbore (σr).
- Hoop stress acting around the circumference of the wellbore (tangential), ($\sigma\theta$).
- Axial stress acting parallel to the well path and additional shear stress components (σz).

At the same context, the borehole instability can be detected by using logging tools as resistivity log, gamma log, conductivity and sonic logs, however these tools should run in the same borehole for many times, in order to detect the changing of reading especially in shale rock.

For instance, when shale's compounds touch by filtrations fluid of drilling mud, which tend to swell and decrease their strength. These changes are related to cat ions exchange capacities which effect on initial electrical resistivity. The swelling rate of shale by hydration depends on the initial structural of it, because the fractured shale is much weaker than un-fractured, and of course the electrical properties will be differed, when it has had weaker planes.

These planes that will be saturated by invaded water, which can be detected by using logs tools. (Bradely et al., 1987). See figure (2-6).

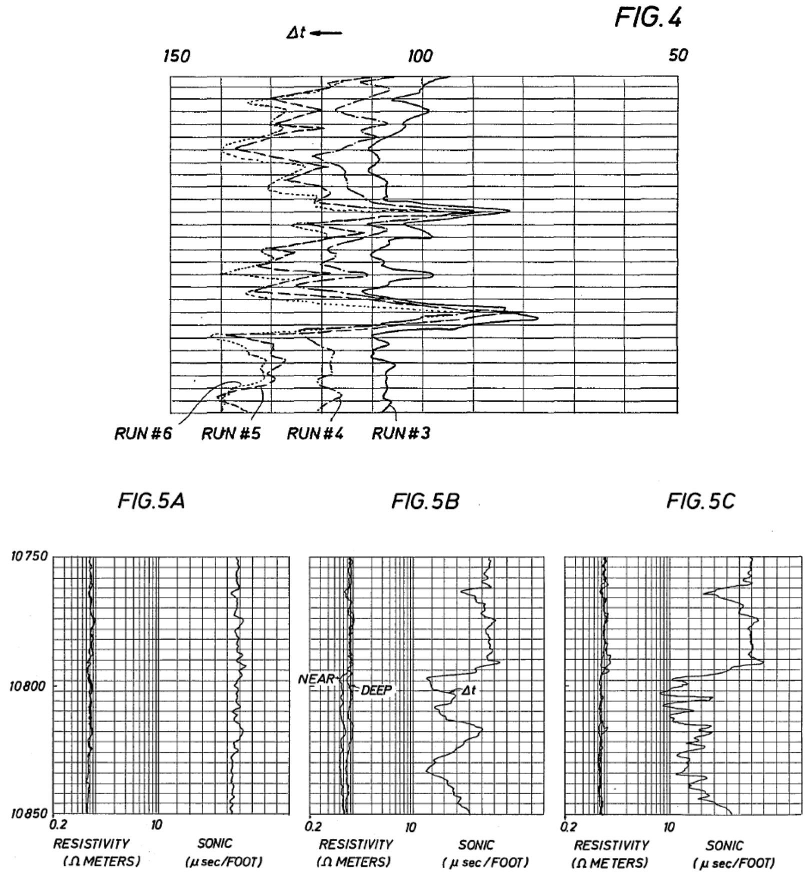


Figure 2-6 Detecting borehole stability problem by using logs tools.(Bradely et al., 1987)

However, the traditional logs tools (resistivity, gamma ray, porosity ...etc.) are able to detect the orientation of breakout, and then the in situ stresses, on the other hands, the developments of these tools are excellent, that represent in the new ultra- sonic image tool that can easily detect the direction of minimum and maximum horizontal stresses, based on, where breakout will occur. See figure (2-7). This tool is very effective to discover the fractures and breakout too.

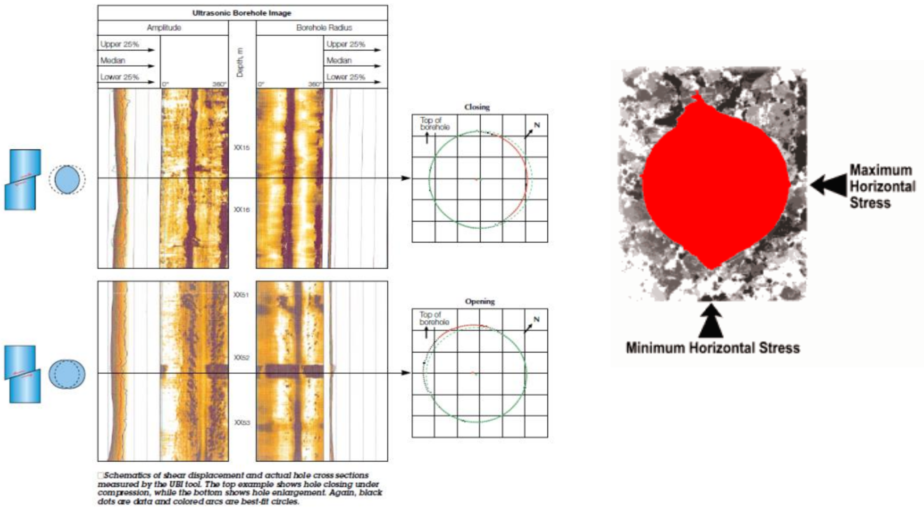


Figure 2-7 borehole breakouts with orientation of horizontal stresses (Lee et al.,1993)(Addis et al .,1993)

This tool is considered, one of other tools which support the expanding in the drilling operation by using innovated technology ,which are being applied in the underbalanced drilling, high pressure jet drilling, re-entry horizontal wells, and multilateral from single well, all of these have been shown lot of borehole instability issues. See Figure. (2.8) (Tingay et al., 2008).

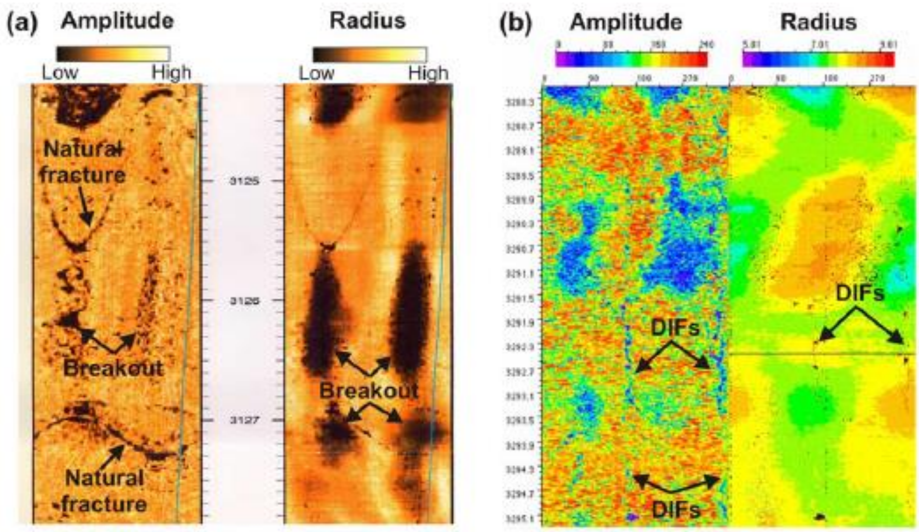


Figure 2-8 Example of breakouts and drilling –induced fractures (DIFS) observed on acoustic image logs.(a) Ultrasonic Borehole image log.(b) Tele viewer logs show DIFS orientation. (Tingay et al., 2008)

If, a rigid body is subjected to the stresses, they will generate shear stress and normal stress within the body. (Addis et al.,1993), an imaginary plane at an angle θ to the principle stress $\sigma 1$ will have a normal stress σ and a shear stress τ acting on it. The normal stresses push the surface of the planes together, while the induced shear stress τ tends to cause the surfaces of this imaginary plane to slide relative to each other. When the shear stresses exceed the strength of the rock, then the rock will fail. The shear failure is created by difference between hoop stress and radial stress (distorted stresses), and this stress should not overcome the failure strength envelop, on the other hand, the tensile failure which causing fracturing is controlled by the hoop stress, which should not be exceeds the limit of the tensile strength of the rock. Different failure criteria can be used to create failure envelope.

2.2. Overview of rock salt behaviour

Rock salt is considered as special soft rock, because their characteristic behaviour generally and in the drilling operations specifically. The rock salt is an invaluable natural resource that forms major deposits in evaporite basins around the globe. See Figure (2-9) (Hereema et al., 2009), in suitable geologic settings, such as rapidly subsiding Gulf-of-Mexico-type basins, salt responds to gravitational forces by flow to form a wide variety of structures, many of them are extruded overlying sediments (Jackson et al., 1986). Decades ago, the study of the mechanical behaviour of salt was driven by the need to design salt mines and to maintain their stability. The mechanical properties of salt rocks (evaporites with halide components) have been a major focus of studies, and storage applications come into play for oil and gas underground storage as well as for other fluids and solid wastes such as naturally occurring radioactive wastes and oilfield wastes in the USA and Canada. The main features of salt when it is used for storage, which it keeps most of their properties constant for long terms. These properties are long sealing characteristics and rheological response of it under stresses. So the important material and risk which is stored inside the salt caverns, requires good understanding basic rock mechanics to the salt rock. The geo-mechanical properties of rock salt and salt deposits are vary because the different of their origins, mineralogical digenetic history and etc.

Figure 1. The major salt formations of the world (from ref. 9) together with the location of the Great Rift Valley in Africa.

Figure 2-9 the major salt evaporates deposits in the world (Hereema et al., 2009)

There are different structures types, which can find the rock salt in nature, which has been taken big attraction by petroleum sector, because they affect directly on petroleum traps and caves for storage. The shape of these structures have been constituted by salt dynamic movements, which can transform a tubular salt body into non-diapiric rollers, anticlines, and pillows; into diapiric walls, stocks, massifs, and nappes; and into extrusive domes and salt glaciers.(MPA. Jackson et al., 1986).The most famous structures which have been under researching, are salt domes and inter-bedded layers ,for instance for the dome as, in Gulf of Mexico fields.

On the other hand, the other type is the inter-bedded with other rocks, which some time has big heterogeneity, with strong anisotropy.

Part of the published papers have mentioned, that the thick homogenous rock salt deposits without inter-bedding ,are not common ,and areas of extensional strain diaprisim are limited (e.g. USA Gulf Coast ,offshore Nova Scotia ,North sea Graben and Northwest Germany Basin, Pre-Caspian Basin in Kazakhstan).(Liang et al., 2007). It was considered; that the anhydrite, shale, salty mudstones, and carbonates are most commonly to inter-bedded rocks with salt rock.

Furthermore, the heterogeneity is focused in the vertical direction, and so on, the mechanical properties of bedded salt deposits are different from of the almost pure rock salt (NaCl).

Most items which have been covered of the rock salt behaviour are classified into four categories:

1. Thermal expansion.
2. Elastic deformation
3. Inelastic deformation
4. Failure.

The thermal expansion and elastic deformation data have been shown that does not be different significantly from site to site; while inelastic deformation and failure vary dramatically in different sites. The contribution of each of the four categories to observe behaviour depends on variables such as temperature, stress and deformation history.

2.2.1. Thermal expansion

The rock salt shares most of materials and rocks, when exposed to heating; the expansion will be in all its directions, the simplest way to evaluate this effect, by depend on linear thermal expansion which gives the change in unit of length per unit of temperature at constant stress, as it has shown mathematically: (Senseny et al., 1992)

$$\alpha = 1/L * (\partial L/\partial T) \quad \ldots\ldots \text{(2-2)}$$

Where α is the coefficient of linear thermal expansion, L is the length over which expansion is measured and $(\partial L/\partial T)$ is the partial derivative of length with respect to temperature at constant stress.

It was studied effect of temperature on rock salt by using coefficient of linear thermal expansion under different temperatures and pressures. (Li et al., 1981). See figure (2-10). The figure has shown in temperature range (50-70) C, the coefficient of linear thermal expansion change do not effect too much through this range , however the effect is clear to high range of temperatures, on the other hand this effect reflect the changing in the axial direction, while the most boundary value problem experiments were done under plain strain condition. The figure has shown also, the pressure effect when will be at high value (25 Mpa) to the same range of temperature.

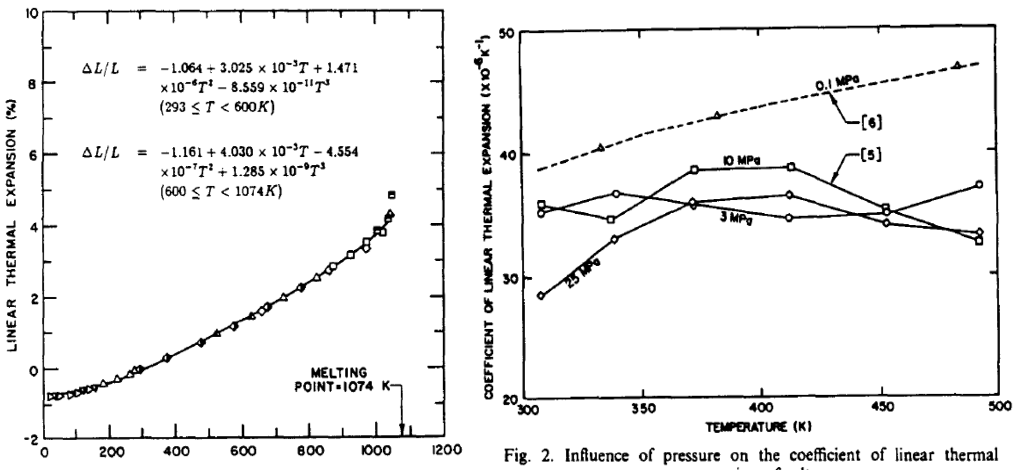


Fig. 2. Influence of pressure on the coefficient of linear thermal expansion of salt.

Figure 2-10 temperature versus linear thermal expansion (%) ,as well the stress(Senseny et al., 1992)

2.2.2. Elastic deformation

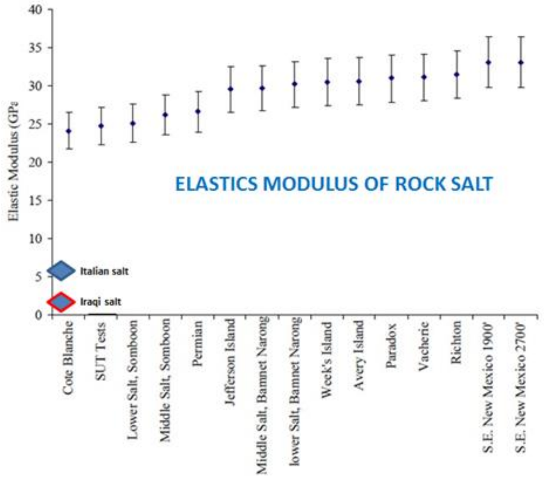
Most material, when will be under stress, this stress create wave, that will penetrate the micro structural system, and then the material will respond for this stresses wave by changing in the equilibrium system. The rock salt respond for this stress wave by a crystal lattice distorts (displacement), which would be faced some resistance from internal bonding. On the other hand, if this stress will be removed, these interatomic bonds return to equilibrium position before stressed. This recoverable deformation is elastic deformation.

Most of the elastic deformation of rocks has shown linear; this linear behaviour can be described by hook law.

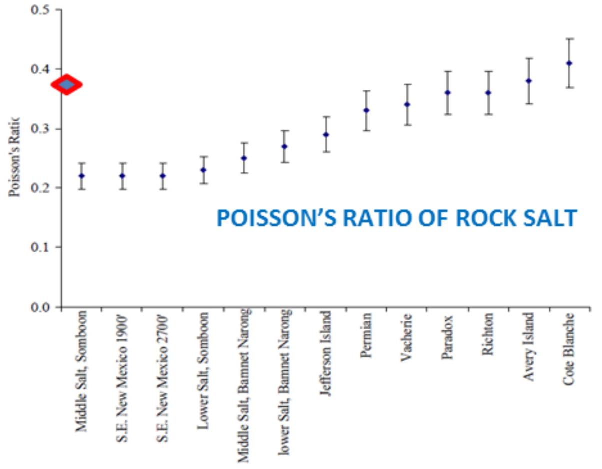
$$\epsilon^{e}_{ij} = (1/E)*[(1+v)*\sigma_{ij}-v*\sigma_{kk}*\delta_{ij}] \text{ ....(2-3)}$$

Where (ϵ^{e}_{ij}) is elastic strain, (E), it is young modulus, (v) it is Poisson ratio, and (σ_{kk}) it is component of stress tensor.

Generally, this elastic behaviour is assumed to be isotropic, furthermore the elastic constants for salt are nearly independent of the source of the salt; it was collected those elastic properties, the differences not too much. See figure (2-11) by (Wetchasat et al.,2002).



Comparisons of elastic modulus of salt from vary sites. (after Hansen et al., 1984; Plookphol, 1987; Boontongloan, 2000; Fuenkajorn and Wetchasat, 2001).



Comparisons of Poisson's ratio of salt from vary sites. (after Hansen et al., 1984; Plookphol, 1987; Boontongloan, 2000).

Figure 2-11) elastic parameter of natural rock salt for different locations in the world (Wetchasat et al .,2002)

However, the Temperature has effects dramatically on elastic deformation, the stiffness decrease when temperature increases, the Young modulus will decrease too.

The rate of decreasing in Young modulus between (-0.04 to -0.016 GPa/K) has been given (Li et al., 1981), as well it was reported the change in shear modulus to be (-0.016GPa/K), (Frost.H.J 1982). Furthermore the Poisson ratio will not be affected by the temperature of one repository (Pfeifle .W.T et al ., 1983).

The elastic deformation is independent from stress because during cycles of loading and unloading the slops are the same ,see Figure (2-12),the figure has shown clearly for two uniaxial compressive tests ,that were done for the Italian salt, with different strain rates, which is meaning, there are no shearing stress effecting on elastic parameters. Farther more, the other properties of the constants elastic deformation, are independent from history effect.

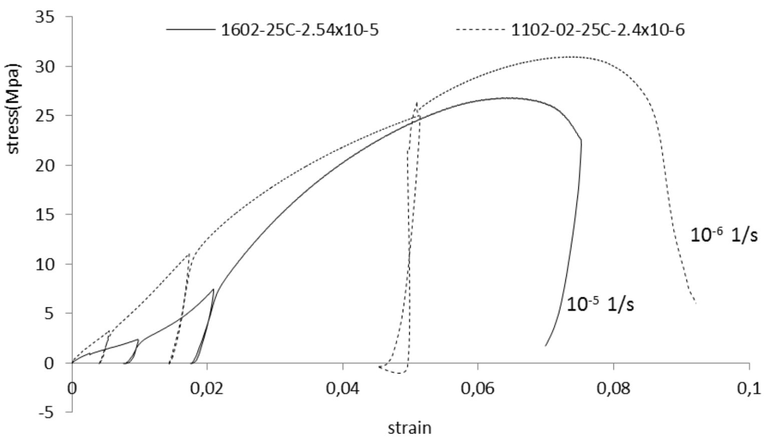


Figure 2-12 typical stress-strain curves for Italian salt through multistage tri-axial test showing linear load unload behavior.

2.2.3. Inelastic deformation

Generally, the inelastic deformation covers the limit, which starting after yield point, however it covers wide range of different behaviours, which variety depending on type of rocks. Most of these behaviours connect with one truth; these deformations are permanent or irreversible.

The rocks in general which, have inelastic deformation that depend on their surrounded conditions as ,temperature, confining pressure, axial load, humidity...etc. Most of rock show brittle inelastic deformations, while some part as rock salt shows ductile deformation which will be occurred under high confining pressure.

In another word, the inelastic deformation can be divided into two types, after yielding point; permanent deformation (homogenous plastic deformation), that will be led to a fracture at some value of permanent strain.

The other type is distinctive with macroscopic fracture that will start at the yield point and then cataclastic deformation (frictional sliding) occurs in post yield region.

The ductility is classified in the first type, which is affected by confining stress (increasing by increase σ3, and decreasing by σ2) (Mogi et al., 1981). the rock salt is characterised by ductile behaviour, this inelastic deformation behaviour refer to defect in part of micro-structural fibre (lattice), and this defect is considered the main reason to cause a dislocation, actually it was thought the reason behind this behaviour is impurities, which is responsible for micro-cracking because the stiffness difference of these impurities compared with origin rock, will act as stress concentration of shear.

Furthermore, most of impurities in rock salt will be at grains boundaries (Liang et al., 2011). However, it might be the impurities locates in sub grains, which effect directly on the inelastic deformation (creep), depending on spatial distribution for that reason ,it can see different behaviour of deformation for different rocks salt under the same conditions test (Hunsche. et al,.2003).

2.2.3.1 Effect of temperature

The temperature is considered the one of most important factors which effects directly on inelastic deformation of rock salt. It changes the physical and mechanical properties (compressive strength, axial strain increase by increasing temperature) as well, the behaviour of rock salt become more ductile. Different researches were published (Hunsche et al., 1990), (Sriapai et al.,2012), which have been shown this effect, most of mechanical properties as uniaxial compressive strength will decrease by increasing temperature. See figure (2.13) uniaxial compressive test for Italian rock salt comparison with Thailand rock salt. (Du et al., 2012)

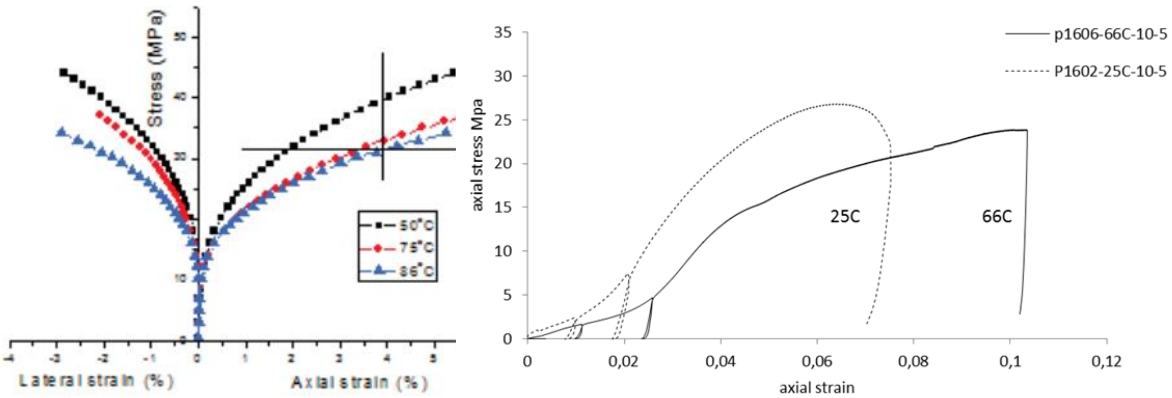


Figure 2-13 influence temperature for creep deformation of two type tests for Thailand rock salt, and for Italian salt.

However, the reason behind this behaviour is connected by micro-mechanic of rock salt. There are different types of dislocation creep mechanics (climb, cross-slip, and glide), which are activated by atomistic activation energy and activation volume associated with solid state flow under dislocation creep. (Muhammad et al,.2015)

On the other hand, some published papers that have explained the inverse behaviour of the thenardite rock salt, when it will be exposed for temperatures. It was mentioned, that the axial strain at failure increase (1.55) times when temperature increase from 20 C to120 C, and 2.78 times at 20C when temperature 180C. (Liang et al., 2006). See figure (2-14)

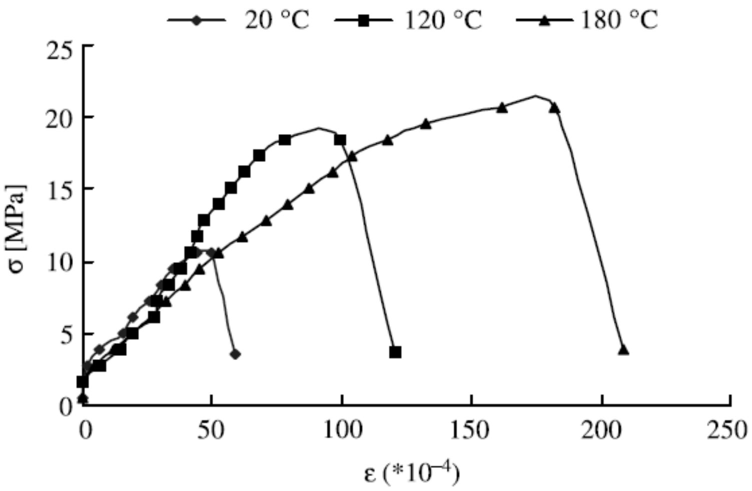


Figure 2-14 stress-strain curves of the rock salt during the uniaxial compression test at 20C, 120C, 180 C respectively (Liang et al., 2006)

There are different micro-mechanics processes happen, when the temperature increase.

The general view for salt behaviour becomes more ductile, which is thought the reason referring to crystalline plasticity dominates intra-crystalline micro-cracking which is more sensitive for temperature than inter-crystalline micro-cracking (Liang et al., 2007); despite there are long standing dispute about, which micro-mechanics processing that control the inelastic deformation for the range of temperature between (25C-350 C), as well confining pressure and strain rate (Muhammad et al,. 2015). Furthermore, at low confining pressures, when micro-cracking can contribute into the deformation, the crystalline plasticity will be clearly appeared.

The high confining pressures have significantly effect that will discourage the micro-cracking, due to decreasing the tensile stresses (decreasing bulging) that leaded to less dilatant deformation in the specimen, therefore at fixed shear stress, the dilatant inelastic strains will decrease as temperature increases. The micro-cracking was appeared clearly in uniaxial test, and the reason for that refers to the mismatch in stiffness in neighbouring grains that have different crystallographic orientation.

There is non-linearity even under hydrostatic stresses; volumetric strain can be divided into two parts, irreversible part which starting from zero till the stress when, reversible volumetric strain will be start. See figure (2-15)

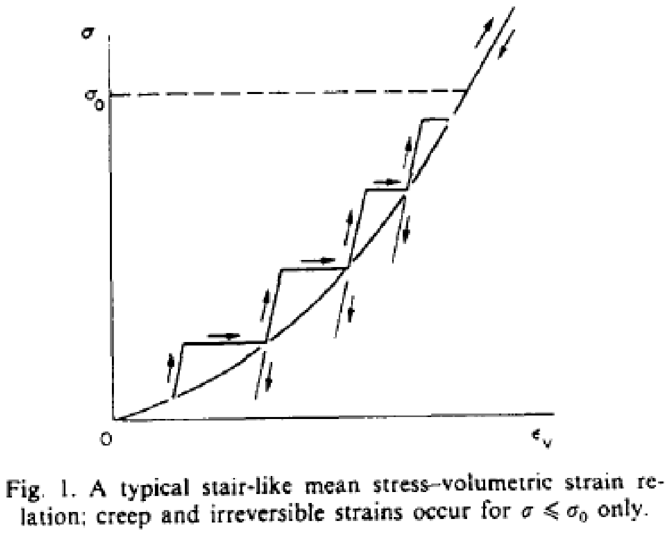


Figure 2-15 volumetric strain vs. hydrostatic stresses (Cristescu et al ., 1987)

The temperatures dramatically effect, even under hydrostatic test. Some part of literatures which have shown, there was not big effect when the temperature changed between (25 ˚C- 50 ˚C), as it can see in table for compressive strength vs. temperature. However, at this range, the Italian rock salt has shown dramatically differences of deformations, even for hydrostatic tests. See figure (2-16)

Table 2. Influence of temperature on unconfined compressive strength

Recovery depth (ft)	Compressive strength (MPa)	
	20°C	50°C
2604	26.3	—
2606	—	29.0
2630	27.1	—
2632	—	25.9
2662	—	30.7
2665	27.9	—
2685	34.2	—
2688	—	26.5
Ave ± SD	28.9 ± 3.6	28.0 ± 2.2

Lower San Andres Unit 4 salt from the J. Friemel No. 1 well.

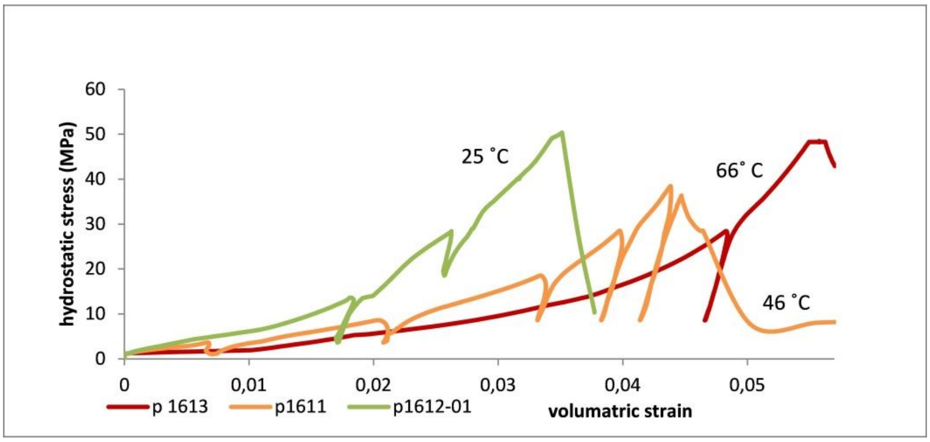


Figure 2-16 compressive strength vs. temperature (Senseny,et al.,1992), hydrostatic test for the Italian rock salt with different temperature

Even the hydrostatic tests were done by assuming the volumetric strain equal three times of axial strain, the figure has shown non linearity of volumetric deformation especially for low stresses till the value (15 Mpa) at 25C, the volumetric deformation become linear (Cristescu et al., 1987), and this value it is seemed increase when the temperature increase, (17 MPa), (20 Mpa), for 45C and 66 C respectively.

2.2.3.2 Effect of confining pressure

Here, it's appeared another factor which effect on the inelastic deformation, it's the confining pressure, this factor affects significantly in range extend between (0 Mpa) to (5 Mpa). For (23 C), and after 5 MPa of confining pressure ,there is effect, but is not too much as it can see in the figure (2.17)

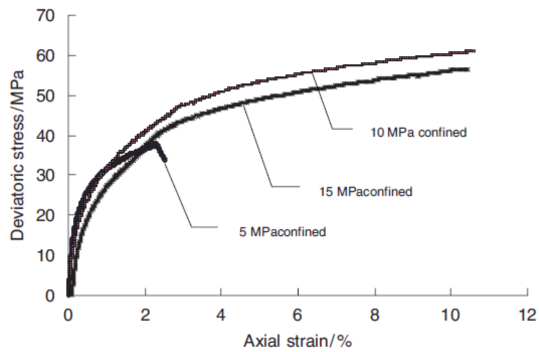


Fig. 6. Halite (rock salt) stress–strain curves under different σ_3.

Figure 2-17 Axial stress difference as a function of percentage axial strain for Jefferson Island salt (Liang et al., 2007)

There is other behaviour of rock salt which connecting with dilatancy under confining pressure but with temperature. Part of experiments was performed to discover this behaviour (Peach et al,.2001), at low confining pressure (3MPa) accompanied with high temperature after elastic deformation, the specimens have shown work hardening under constant strain rate, while the specimens under (6.5MPa, 10 MPa, 30 MPa), have shown after work hardening, followed by steady state creep. See figure (2-18).

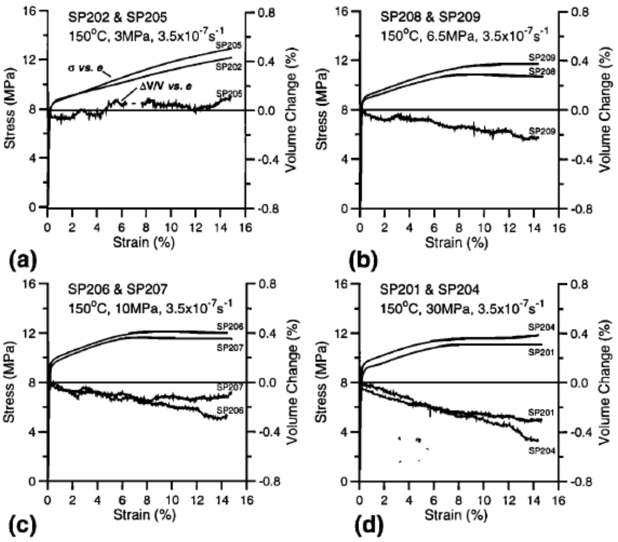


Figure 1. Representative stress versus strain and volume change versus strain curves obtained for samples deformed at confining pressures of (a) 3, (b) 6.5, (c) 10, and (d) 30 MPa. Note the continuous work hardening behavior and net volume increase obtained at 3 MPa confining pressure compared with the steady state flow and compaction obtained at higher pressures.

Figure 2-18 rock salt behavior under confining pressure companied by high temperature effecting. (Peach et al,.2001).

Other experiments were done on synthetic rock salt to see the effect of confining pressure on dilatancy at (23 C),(Peach et al,.1996) , the summarized for these tests has shown in the figure (2-19), it's clear at confining pressure (20MPa), there was no signs for dilatancy.

It was reported, at confining pressure (17.5 MPa), the dilatancy was suppressed (Peach et al,.1996).

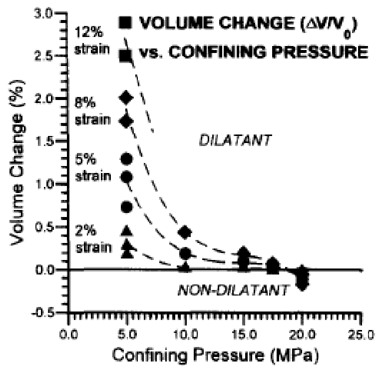


Fig. 5. Volume change versus confining pressure data, at constant strains, for all tests performed. The transition from dilatant (positive volume change) to non-dilatant behaviour of ~18 MPa is clearly visible.

Figure 2-19 effecting confining pressure on dilatancy at 23 C (Peach et al,.1996)

2.2.3.3 Effect of shear stresses

The most important point that are mentioned a lot, that the inelastic deformation is strongly influenced by shear stress (stresses difference), many constitutive models assume that the shear stress dependence is a power (n)

The inelastic deformation mainly depends on shear stresses by nonlinear relationship. Most of constitutive models that use exponent for stress difference ranging between #2 to #9., it is clear to see that in the figure (2.20) that has done for Italian salt.

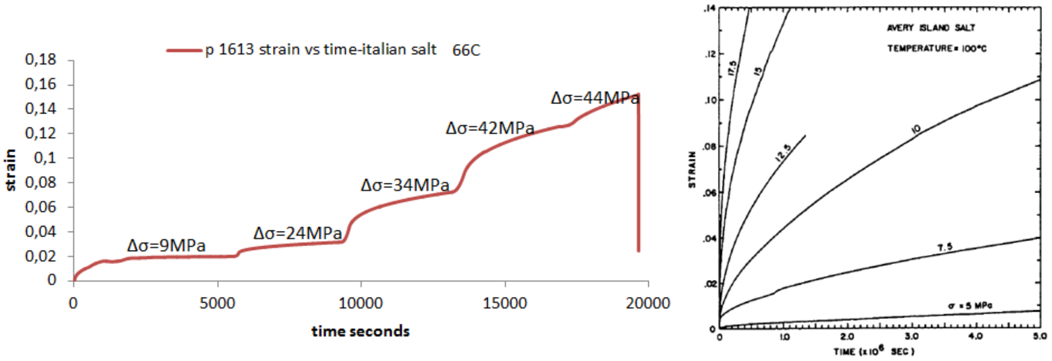


Figure 2-20 influence of stress difference on deformation of Italian rock salt at temperature 66C (left), influence of stress difference on creep deformation of salt(Senseny et al .,1992)(right).

2.2.3.4 History effect

The other important factor which affect to the inelastic deformation, is the history, the rock salt shows feature faded memory. The temperature, stress, and strain rate, are the most features affecting directly on the history of creep of salt. It was divided the history into two part distant and current, the most effect history is current than distant. The transient creeping has shown strongly dependence on the current history, which is obviously seen when change the stress or load, by responding the strain rate. On the other hand, the steady state creep has shown faded memory dependency (stress, strain rate, and temperature).Finally, moisture effects on inelastic deformation, here this factor, is more active and can manipulate in one crystal of salt (more ductility) than poly-crystals, as well the moisture affect dramatically for creep test at low confining pressure rather than high confining pressure, because when dilatancy appeared, that give open way to moisture effect.

Furthermore, when unconfined creeps test, it can see the transient creep effect directly by moisture rather than steady state creep.

The moisture affect clearly when the strain rate (10-7 s-1) for compression tri-axial relaxation tests, it was seen under this low strain rate, the stress required to deform the specimen was less, when the specimen was saturated, while high stress in dry. (Spiers C.J et al., 1988)

In brief, the inelastic deformation is strongly dependent on the temperature, stress, loading rate, as well history, furthermore the moisture when dilatancy will work. The temperature plays big role in ductile crystalline plasticity more than the brittle inter-crystalline micro-cracking. The increase shear stress will lead to increase the inelastic deformation (high inelastic deformation rate), however, increasing confining pressure reduce the inelastic deformation. (Especially brittle deformation)

2.2.4. Failure

The rock will be failed when the applied stress reaching to a certain limit, and this limit depend on total stress state, not only the stress in one direction but, for every stress path, that can represent as a point in stress state space.

So every type of rock has what is called failure surface, which can represent in tensile, shear and compaction failure, and for each one of these envelop the stress path, extend from tensile, tri-axial to hydrostatic tests.

However a rock under compaction stage able to support a load even after reach to failure on this surface, while the tensile and uniaxial shear failure the rock do not support a load anymore. .

Usually, the material is described when reaching to failure that cannot bear more loading, till to loss completely the ability to support the load.

Generally, this stage reaches after the material will pass the strain softening (localizing), that can see in laboratory, the peak of the strain-stress curve (constant strain rate), or starting tertiary deformation in constant stress (creep).

As in inelastic deformation, there are different factors which effects on this deformation at failure, as temperature, strain rate, stresses difference, humidity, inter-bedded layers…etc.

The other important factor effect on failure state of rock salt, especially on bedded rock salt, is interlayers with other rocks, as anhydrite or mudstone. See figure (2-21) (Liang et al., 2007)

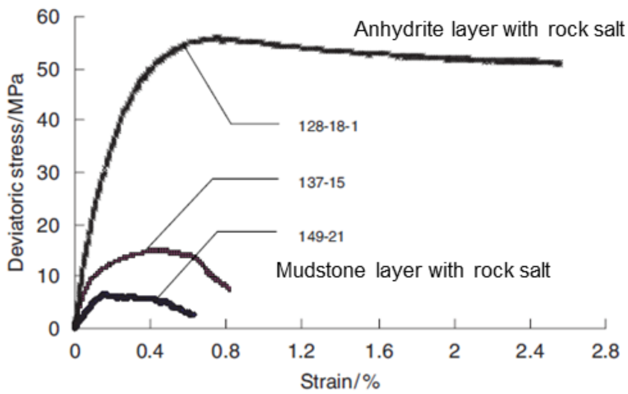


Fig. 12. Stress–strain curves, bedded salt with different interlayers, $\sigma_3 = 10\,\mathrm{MPa}$. The two lowest curves are mudstone–halite and the upper one is anhydrite–halite.

Figure 2-21 effect of inter-bedded layers of failure of rock salt(Liang et al ,.2007)

More important factor, which effect directly on the failure deformation, is the shear stress when will increase and to be close to the failure that will increase too, because the confining pressure support the rock salt and then prevent it from failing.
The failure mode and time that act to complete the cycle of the effect shear stress on failure.

The time entering in strain rate which with shear stress, control the behaviour of ductile –brittle failure, as it can see the figure (2-22).

the figure are very interesting to describe this behaviour, it’s clear that the failure will be at high stress difference, when the confining pressure will be high enough, and the same time, the combination acting of the strain rate and the shear stress create line which was labelled as steady state line, which means, the failure will not occur above this line.

The shear stress relation with mean stress depends on the stress state, for example the values of failure in tri-axial compression test are more than tri-axial extension test., and the result has been clear in the figure (2-22)

In addition, most literatures has shown the ranged of strain rates about (#10-4 to # 10-6) which most of experiments that have been doing, it will see later the effect of strain rate on the strength of the rock salt, in tensile and uniaxial compressive tests.

In brief, when increase the pressure, temperature and decrease the strain rate (or rate of loading); it will get large strain without reach to failure.

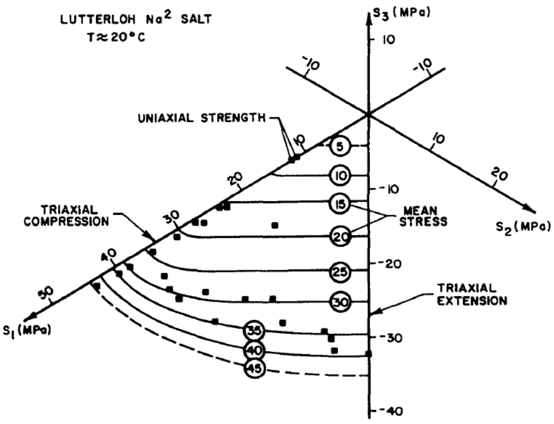


Figure 2-22 results of failure experiments plotted on the octahedral (π) plan. Shear stress at failure is proportional to the distance from center (Senseny 1992)

2.2.5. Micro-Mechanics

It should be mention for other part, and it is important because its direct relationship with rock salt deformation, this is the micro-mechanic, which follows the deformation from the atomic scale and gives the analysis behind that deformation from physical point of view.

Generally, it can say, the deformation consists of two conversely processing, hardening and recovery.

The micro-mechanics phenomenon is studied the evidence of these two mechanisms by using different types of optical view of substructure, and compare these evidences with theoretical deformation interpretation.

The observable microstructure is the most important and complicate. There are lot of factors which effect on this mechanism as temperature, humidity, and stress difference.

The micro-evidence depends on how much strain can be applied in order to be in one of this mechanism. , the rate that each mechanism work, depends strongly on the pressure and temperature, which was introduced to create mechanics map for rock salt. See figure (2-23) in the salt deformation. (Munson D.E et al .,1979).

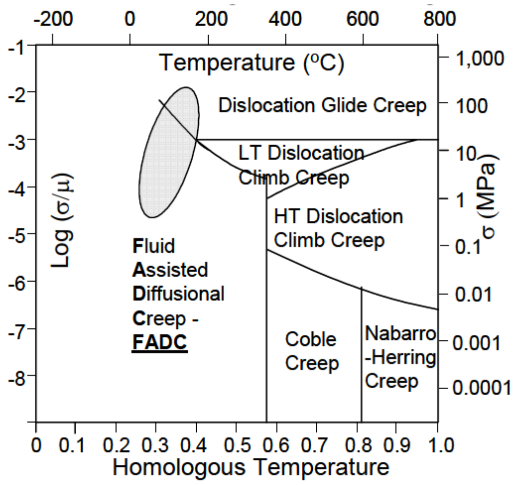


Figure 2-23 Deformation mechanism map for WIPP salt based on Munson D.E., Preliminary deformation-mechanism map for salt (Dusseault et al 2007)

When the stress and temperature increase, the strain increase too, and that lead to the first substructure change (meaning the first stage of stress and temperature as well as, the strain) then, the dislocation density will be increased. If the strain increase slightly (less than 0.01), the salt will be in linear glide bands, much more increasing in the strain, the individual bands become wavy and cross link, and when temperature increase more (third of melting temperature), these bands will be elongation(polygons).

Generally, it can be listed the sequence of microscopic processing inside the salt coincides with increasing of temperature as well large strain, as below:

1. Glide.
2. Cross slip.
3. Recrystallization.

The ellipse in the graph represents the drilling operation area within micro-cracking processes in the rock salt. (Dusseault et al .,2007)

2.2.5.1 Dislocation Glide

This process occurs in atomic plane of crystalline, when the lattice has some defected, later if this crystalline will be expose to differential stress, causes dislocation.

There are six groups of expected planes which happen this dislocation, however the first activated plane are named close-packed group <110> which consist lots of slip planes, but the famous slip plane family are {110} . by using thin section and under cross polarized light, the dislocation glide will show photo-elastic effect along the slip direction {110}, or through linear array of etched pits which has created by of glide.

This mechanism is responsible for strain hardening that occurred in rock salt, by intersection or pile up tangles of dislocation stacks near the grain boundaries or obstacles , as well this substructure characterised by high stress caused by obstacle the dislocation stacks, and if not finding way to relief this stress, will lead to create damage near to this impeding (distort the cubic crystal lattice) or create photo-elastic effect, the final result it will cause decelerating creep (transient creep).See figure(2-24) , this type of dislocation occurs when strain range between (0.01 to 0.1).

Figure 2-24 dislocation glide impede at a boundary grains (J.L. Urai et al., 2008))

2.2.5.2 Cross slip dislocation

This process reflect behaviour of the crystal into rock salt, when the glide dislocation inhibit, (and for any reason as the grain boundary or pile-up by interaction with other dislocation glide band) to release the accumulative strain hardening, by changing the motion to another slip plane or other direction of dislocation that have the same burger's vector.

So, it is recovery processing, to relieve the increasing strains. The screw dislocation is one of the cross slip movement. The cross slip mechanism is considered as separating dislocation. The new separated plane is affected directly by the confining pressure.

The evidence for this processing are wavy deformation band (slip /sub-boundary) structures, and it will be expected to happened at differential stresses above (10MPa) to (15 MPa) (Drury et al., 2007).

This phenomenon has been given the realistic analyses for homogenous plastic deformation of poly-crystalline rock salt, because this processing need to the 5th slip planes. However, in reality it has just two independent planes, because the strain-stress- time curves, has shown completely plasticity without any fracture, strain hardening and steady state creep. So the solution for that trouble is the cross slips processing. The cross slip at low temperature refer to brittle –

ductile transition in most geo-engineering applications. (Senseny et al., 1992) .See figure (2-25)

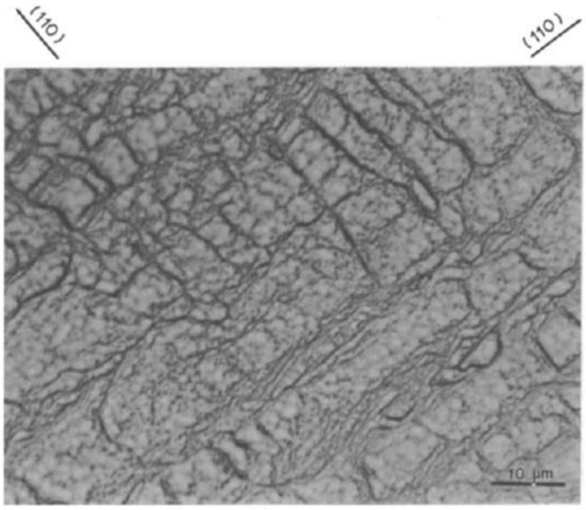


Fig. 18. Etched cleavage chip of Palo Duro Unit 5 salt deformed to 6% strain at 15 MPa and 75°C. The substructure consists of intersecting glide bands.

Figure 2-25 cross slip processing (Senseny et al., 1992)

The dislocation is considered, the main controlling processing for polycrystalline rock salt at range of temperature between (100-200) C in laboratory experiments, which have been shown large strain because these sub-grains processing. This processing was created through grain, the large of these sub grains depend on the differential stresses.

2.2.5.3 Recrystallization (solution-precipitation)

This phenomenon connects with salt saturated water contents between grain boundaries of polycrystalline rock salt, but should be in significant amount. The brine contents releases most stored energy by reduce dislocation density.

The brine contents supports the grains migration, and it is happened even in room temperature, which is called “solution precipitation (pressure solution) “.

The chemical potential and dislocation density are responsible for this migration between old deformed grain and the new growth.

Generally, the migration is companied with sliding and rotation of grains, which led to the compaction of porous salt (Drury et al., 1990).See figure (2-26). So, the pressure solution –precipitation is a creep without plasticity of crystal.

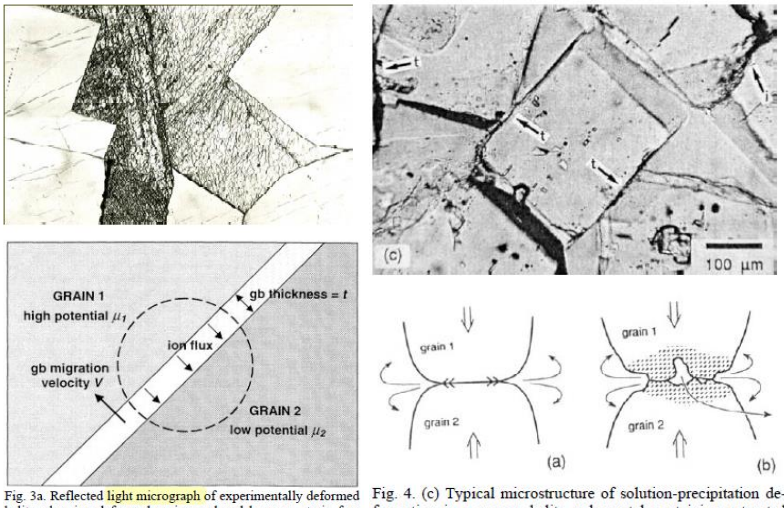


Fig. 3a. Reflected light micrograph of experimentally deformed halite, showing deformed grains replaced by new, strain free grains (Asse Speisesalz, 150 °C, 100 MPa, $3x10^{-5}$ s^{-1} followed by stress relaxation). The grain boundary migration is assisted by the presence of thin fluid films on the grain boundaries, and can take place at significant rates at room temperature. b) Diagram illustrates the principle of grain boundary migration by solution-precipitation transfer across fluid-filled grain boundaries.

Fig. 4. (c) Typical microstructure of solution-precipitation deformation in a porous halite polycrystal containing saturated brine (after Spiers et al., 1990). Diagram shows the mechanisms of solution-precipitation creep without plasticity of the crystals (a), via a thin fluid- filled grain boundary, and (b) combined operation of solution-precipitation creep and crystal plasticity (after Spiers & Brzesowsky, 1993).

Figure 2-26 recrystallization processing by solution precipitation (Drury et al .,1990)

- Rotation mechanisms, which involves creation of new grain boundaries.
- Migration mechanisms which mainly involve grain boundary migration.
- General mechanisms which involve both basic processes.

The recrystallization is considered a recovery processing, which is responsible for strain softening, it can observed that in stress-strain behaviour under constant strain rate or stress rate.

2.3. Well bore stability in rock salt formation

The rock salt has considered one of the important rocks which should be treated with a lot of care when it will be faced through oil and gas drilling operation, in both types' domes or inter-bedded with other formation rocks as shale or anhydrite, most of time, when the rock salt is found, the oil or gas reservoirs are found too.

Large oil and gas reservoirs are associated with salt structures, for instance Domal structures in the Gulf of Mexico .see figure (2-27), Williston basin (Mid US Continent Devonian age) the North Sea (Zechstein age salt emplaced in the Cretaceous), Iran (Zagros salt plugs, which in some areas outcrop), Brazilian and West African offshore basins, and other areas, and it provide targets for exploration oil and gas.

Sub-salt resources are found in the GoM salt tongue regions, in large areas in Kasakhstan (Kashagan and Tengiz), and in other areas. These may involve drilling through as much as 1500-2500 m of salt to depths of 5-9 km (Dusseault et al., 2007).

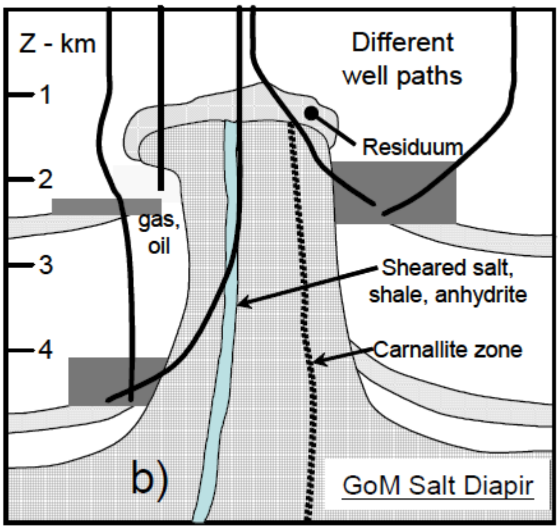


Figure 2-27 deep diapiric structure GoM, Some Conditions Encountered in Drilling Salt (Cook et al,.2007)

The geological sedimentation environment, shows the salt would be under some thousands of meters below the surface, so this depositions will be under high stresses (overburden rocks), and temperature, however, the rock salt was classified as soft rock, furthermore sometimes these geological deposition is being coupled with active tectonic movement resulting from movement of earth crust, which adding more forces on this type of plastic rock.

So, in equilibrium state when there are not disturbed for rocks by any external factors as drilling however, when it will be in active tectonic zone, this type of area are famous with a fractures and faults as result, while the salt show the plastic deformation or flow through fractures, farther more it try most of time, to be upward movement by effecting the difference of densities comparing with other rocks. See figure (2-27) .So this is a big challenge for oil industry especially drilling sector.

Generally, the stability of a deep borehole is basically controlled by four factors:

- The in-situ state of stress
- The geo-mechanical properties of inter-bedded rocks
- The drilling fluid
- Time

The first two factors should be determined as exactly as possible. The other two factors should be modified and comprised between them. So, as quick as possible, the borehole should be drilled with a precisely controlling of a mud weight companied with the fastest rate of penetration, which will be lead to less borehole closure creep deformations.

Despite of the rock salt has less permeability, which mean less mud filtration effected but from micro-mechanics point of view, even less amount of brine contents (filtrated drilling mud) but it will be more affected on borehole closure creeping.

On the other hand, the high density to the mud weight, try to supress creeping tending of the salt , however it might be risk to fracturing the other rocks that shared the hole with rock salt. However, the confrontation of the rock salt while drilling is not considered a serious problem, from practical point of view because, if the drill pipes will stick, it easy to release it by washing the stuck zone with fresh water, even casing pipes. However the big challenging may be faced at cementing operations, because most cementing of borehole which has washed rock salt, it will be not good.

These new circumstance will be paved to another problem (collapse casing).

So, it's a big challenge, especially, a decision to setting casing pipes at the end thickness of the rock salt. The transition zone between rock salt and other type of rocks which share the borehole with rock salt is a another problem during drilling the borehole. This zone is characterized by different mechanical properties, which can consider as weak zone, (rubbles).

So, all these challenges have been increased the adventures, as well temperature, stresses differences, brine inclusion, humidity, tectonic activity…etc. The best solution to overcome this situation is put plan that was designed on good analysis and predication of borehole closure during drilling and after, as mention before.

Most of oil wells that have been encountered rock salt are used inert drilling mud (oil base mud, or salt saturated mud). The both do not have any chemical effecting; however, they take responsibility about humidity, as well increase fluid inclusion during salt deformations.

Furthermore, the rock salt in the borehole will affect in indirect way, the rubbles zone (transition zone) is considered the other big challenge that will lead to lost circulation problem, which later leads to may be blow out.

The first target of any drilling plan is to be far from lost circulation, then blowout. So, for those two expected problem should mitigated.

2.3.1. Assess borehole stability by direct methods.

The concentrated stresses around the borehole wall contribute in borehole instability, which will be developed depending on the ratio between rock stresses on strength material of rock, if this ratio is so high, the rock will be cross the elastic limit, passing inelastic deformation till failure. The responding of rock to these concentrated stresses will be degradation on surrounded rocks for borehole wall, or will be changed the circular shape of borehole. This degradation will take different pattern, from falling pieces of some type of rock and other closure of borehole.

As well, the borehole closure opposite the rock salt section is the target that should be checked with predicated constitutive model. It can benefits pre-exist geological information by using different methods. Some of these methods was mention in chapter one, as using electrical logs of wells, a new technology borehole imaging, seismic and electromagnetic sounding …etc. Most of these techniques are based on physical properties. Through Geophysical techniques can be assessed the rock mass for folding, faulting, bedding plane, discontinuity…etc. However, these physical properties cannot be direct way for most mechanical properties of rocks in general, so it should be recovered specimens from interested depth to cover that. It can examine borehole closure during drilling processes by using daily drilling reports, if the borehole will be closure or not? It will be done by precisely checking the drag while drilling, especially front of plastic formation as some type of shale or rock salt. See figure (2-28)

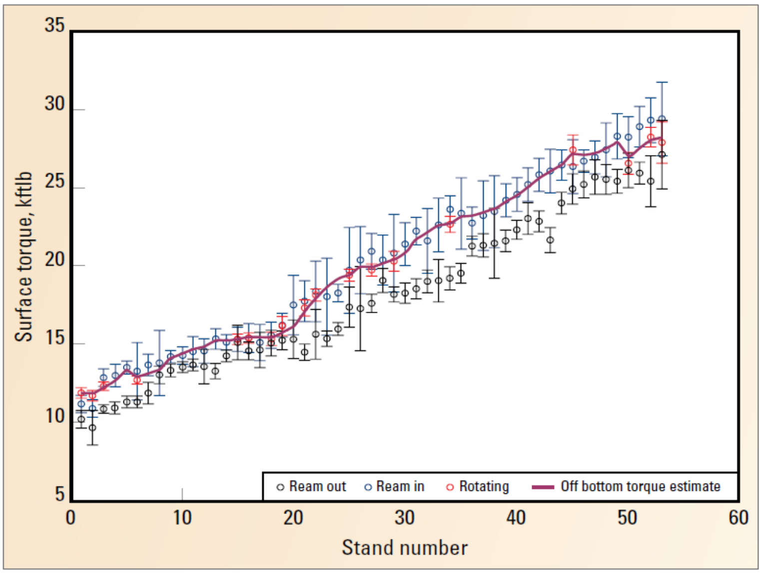


Figure 3: Mean and standard deviation of surface torque are observed in each stand of pipe as a function of the driller's activity (red = off-bottom, pumping and rotating; black = reaming out; blue = reaming in). A Kalman filter estimating the off-bottom torque is shown in magenta.

Figure 2-28 off bottom reaming torque vs. depth (stand =300meter)(Dunlop et al,.2011)

It might be use direct borehole closure measurements by using (calliper logs) rather than laboratory cores testes. However these methods is very expensive, so it can evaluate the running or pulling pipes trips of the hole, dragging for the interesting salt depths

For instance of dragging and borehole closure, it was in oil well in Faquie filed, opposite of a bed of rock salt, the calliper log was running for many times and the different periods, and there was a period of time between them, the result was represented by relationship between differential stress (over burden pressure minus hydrostatic head of mud) vs. borehole closure by calliper log., it is clear ,when the differential stress are less ,the borehole closure will less too .See figure (2-29)

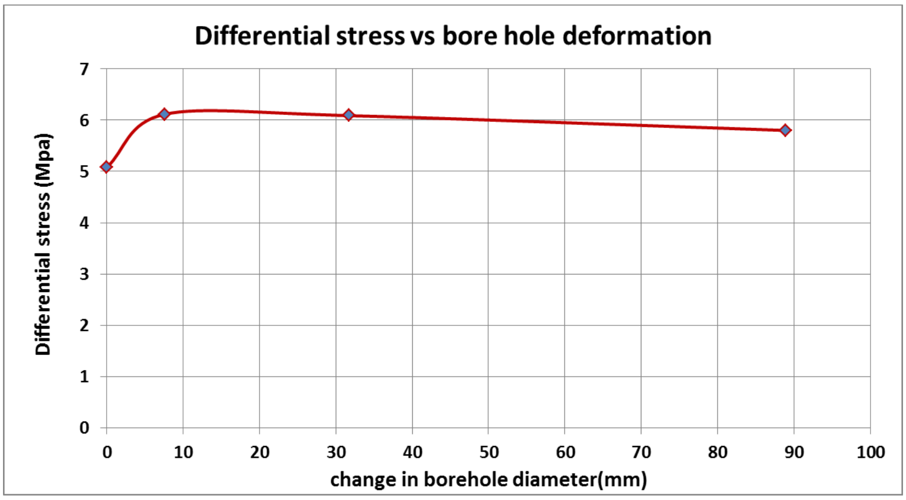


Figure 2-29 Case study in the south of Iraq well. (Fauqi field) ,Stresses difference (Mpa) vs. borehole closure -front of salt (mm)

Nowadays, the new technology can be used as LWD (logging while drilling), or MWD (measuring while drilling), those two methods even, are high expensive to use it, but the benefit is important to evaluate some borehole stability.

For instance, It can be evaluated all recorded logs data (resistivity, density, gamma, calliper, neutron, etc.), for many times to the same borehole.

It is not easy to generalise a specific data from geophysical records, and mechanical core tests for wide rock mass. So, it needs to cover anomalous properties that combine general background of the rock properties and the nature of most probable.

2.3.2. Analystical and numerical analysis .

In general, all best plans are based on a quantification adventure and risk for both open borehole (unsupported) and cased hole (supported) during drilling or production, to predicate a deformation fields around borehole by using effective constitutive laws.

Most of times, it will be sophisticated despite the predicative limitations.

Parts of work depend on perfectly elastic/ plastic models to evaluate borehole stability of general rock, and then calibrated with experimental data which was taken from conventional tri-axial tests.

2.3.2.1 Elastic analysis

It was mention in the first part of this chapter for elastic solution analysis, which will get displacement and stresses based on an infinite circular hole in a homogenous, isotropic, and linear elastic medium. Kirsch's solution is considered the familiar method of borehole instability. Under this title" elastic solution", there are three failure types:

1. Tensile.
2. Shear.
3. Matrix collapse.

The first failure type, the pressure rate affect directly on the type of tensile failure, if the rate is so high, the failure will be merged together in macroscopic phase along the borehole axis's and close to wall borehole, while if the pump rate is moderate or low, the fractures create will be spread and in microscopic pattern, which is preferred from production point of view

The shear failure is the second type of failure, which is classified into two types, active and passive modes, the active one which will be work when the pressure inside the borehole decreasing, while the passive mode , its work when increasing the pressure. There are different criteria that used to describe the behaviour of rock under these conditions as Mohr Coulomb, and Drucker-Prager …etc.

The third type of failure which is connected by the hydrostatic stresses. This type of stresses completely depends on the mean stresses, when these values cross the limit of matrix collapse.

It can see this type of failure through porous rocks, which will be compacted under hydrostatic stresses; however the same behaviour is found even in less porosity rock as rock salt.

It is assumed, sometimes, the elastic solution gives good results, because the time spending for excavation (drilling), is short compare with the time to use this borehole for various purposes. However, some borehole cases are shown problems after the excavation quickly, but generally the elastic solution for excavation stage, which represent by creep associated with stress relaxation, has shown realistic results.

2.3.2.2 Inelastic analysis

The stresses are predicted, by using linear elastic behaviour till the failure, are so high comparing with inelastic analysis. These stresses high concentrated on the borehole wall, was observed, through experiments of a thick wall hollow cylinder and in situ.

Despite the behaviour of rock salt (borehole closure) under these type of experiments are different ,but it can be put under the same classification, because it share the other with factors that effect on inelastic behaviour as stress gradient related to geometric, the intermediated principle stress , stress paths and strain rate.

It was discovered that a strain softening is not able to describe the deformation for deep borehole rocks or even moderated depth, so the elastic models is not enough to cover that deformation because, there are other region that was created which represented plastic area around borehole wall. This behaviour is described in ductile rocks as shale or salt. These two types of rocks have been shown inward movement; even borehole is filled by a mud, and the result will be elliptical shape.

Actually the rock salt is characterized by inelastic deformation, because its time dependent behaviour. It’s deviated from hydrostatic in situ condition even at low stress, and it shows behaviour as a viscous liquids.

The main pattern of inelastic behaviour has been represented by creep because, the plastic deformation has been considered very small compare with the creep, and most time it was neglected, furthermore the thermal deformation is created by thermal condition, it was neglected too, because it was assumed isothermal condition.

However, the creep is considered dependent on time and temperature, and shown viscoplastic deformation that induced by constant load or non-constant load.

The steady state creep is characterized by increasing the strain creep and constant strain rate (work hardening and recovery) ,and application for long term , furthermore, it is stresses ,and temperature dependence, while the tertiary creep characterized by increasing creep strain as well high strain rates, up to failure, short term application.

So, it can be said that the total strain is the sum of elastic (ϵ^{e}), thermal (ϵ^{th}), plastic (ϵ^{p}) and viscous (ϵ^{v}) strains

$$\epsilon = \epsilon^{e} + \epsilon^{th} + \epsilon^{p} + \epsilon^{v} \text{.......... (2-4)}$$

Sometime, the thermal strain was not considered because under isothermal test condition, (.Zhao et al,. 2013)

$$\epsilon = \epsilon^{e} + \epsilon^{v} \text{........... (2-5)}$$

This viscous strain generally is depended on micro-mechanism processes (dislocation), which depends on impurities, inside the rock salt, (Hample et al.,1998), as well temperature and stresses difference. See figure (2-30).

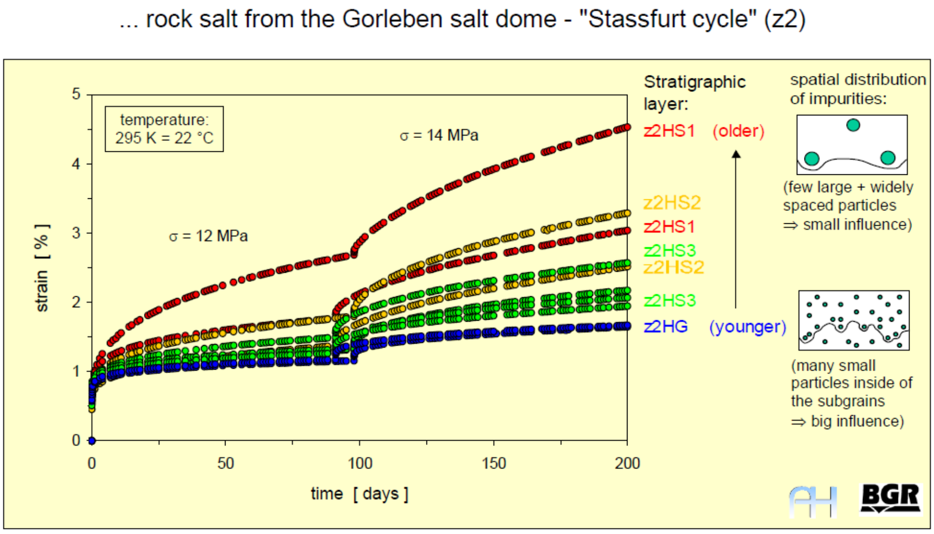


Figure 2-30), effect of impurities on creep deformation for different type rock salt (Hunsche et al,.2003).

It has seen the strong relation between the differential stresses and creep, these stress sometimes, would be hydrostatic, or devaitoric pattern which effects directly on mechanical behaviour to rock salt by reducing the Young modulus and shear, while the bulk modulus is being far from this effect, however if this rock salt would be faced hydrostatic stress path, directly the bulk modulus will be changed. (Fjaer et al,. 2008).

On the other hand, this behaviour is time dependent, it can be seen when apply stages of hydrostatic stress on rock salt for the same period of time, a volumetric strain will be decreased every stage progressing. (Cristescu et al., 1998) .See figure (2-31)

The figure has shown test on a cubic rock salt specimen from the Gorleden salt dome(North Germany) with several hydrostatic loading steps of pure stress(deviatoric stress zero),between the steps the stress held constant about 1.5 hours. a) Volume change $\boldsymbol{\varepsilon_v}$ **vs**. time: b) mean stress **$\boldsymbol{\sigma}$ vs. $\boldsymbol{\varepsilon_v}$, $\boldsymbol{\sigma}$=K. $\boldsymbol{\varepsilon_v}$** Elastic volumetric compression.

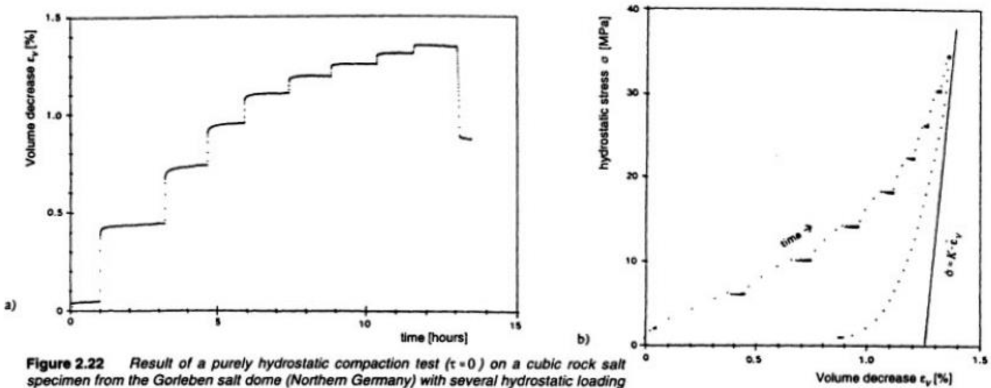


Figure 2-31 volumetric change during hydrostatic stress path for different stages. (Cristescu et al., 1998)

Under the viscous strain, there are three types of creep strains, which will be controlled by reference stress or other named uniaxial yield stress.

This stress separates the two main creep strains primary and secondary from tertiary creep strain.

It has named the first, transient creep, which can be under effect of hardening that leads to decrease strain rate with time, while the steady state creep that characterized by constant strain rate because, this creep is produced, when there is balance between hardening and recovery processing. The result of that creep produce constant creep rate with time, which mainly depending on the density of dislocation and types of dislocation through salt crystal. (Langer et al,. 1982).

The tertiary creep also is named, accelerator creep strain, which is happened when the applied stress is bigger than reference stress “uniaxial yield stress”. The rock salt under this type of strain will be in failure state. The behaviour of rock salt is very complex, but using Von Miss effective stress- mean stress space will help to understand. See figure (2-32).

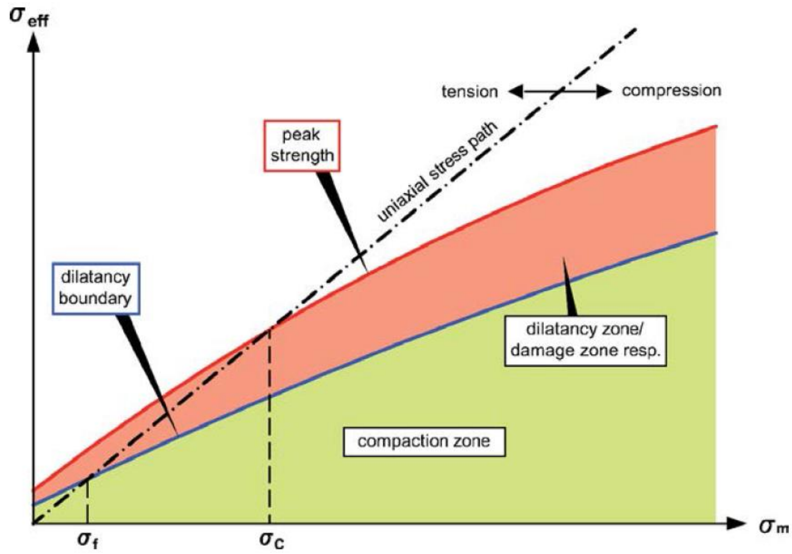


Figure 5.2 Constitutive behavior of rock salt

Figure 2-32 effective (von miss stress) –mean stress space of rock salt. (Wittke et al,.2014)

The effective stress represent the deviation from hydrostatic stress state where, all principle stresses are equal each other, and this deviation is the second invariant of the deviatoric stress tensor.

$$\sigma_{eff} = \sqrt{\frac{1}{2} * \left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\tau_{xy}^2 + 6\tau_{yz}^2 + 6\tau_{zx}^2\right]}$$

$$= \sqrt{\frac{3}{2} * \left[s_x{}^2 + s_y{}^2 + s_z{}^2 + +2\tau_{xy}^2 + 2\tau_{yz}^2 + 2\tau_{zx}^2\right]} \text{..........(2-6)}$$

$$[s] = \left(s_x, s_x, s_x, \tau_{xy}, \tau_{yz}, \tau_{zy}\right)^T$$
$$= \left(\sigma_x - \sigma_m, \sigma_y - \sigma_m, \sigma_z - \sigma_m, \tau_{xy}, \tau_{yz}, \tau_{zy}\right)^T \dots\dots..(2-7)$$

$$\sigma_m = \frac{1}{3} * \left(\sigma_x + \sigma_y + \sigma_z\right) \dots\dots(2-8)$$

The figure has been described important zones which outline the main parts of constitutive models.

- Compaction zone (elastic strain, primary, and secondary strains).
- Failure zone (tertiary strain).

Generally, these zones are separated by two boundaries, one of them is called dilatancy /compressive, and the other is called failure (peak of strength). Under the compaction zone expect to get elastic strain, transient and steady state strain. This boundary can be detected by empirical equation that was done by (Spiers et al.1988, Ratigan et al. 1991) (Van Sambeek et al,.1993) by using standard tri axial test (biaxial), because this boundary can be detected straight by using true tri-axial test for cubic specimen. However, it can be used constant mean stress experiment for biaxial test to get dilatation stresses. Furthermore, using true axial test result and constitutive model which was done by (.Hunsche et al,.2003), that independent of type of rock salt. The rock salt volume will decrease till the dilatancy boundary, the change in volume will be zero, and after this limit the rock salt volume changes will be increased.

Also, it can detect compressive /dilatancy boundary by changing of rate acoustic emission, and seismic wave velocity (Vp, Vs) because when micro-cracking will be created, the physical properties of rock salt will be appeared in acoustic emission, which mean increasing permeability. This limit is not a separated line but it is a domain at which spread when increasing mean stresses (Agergaard et al,. 2009).See figure (2-33).

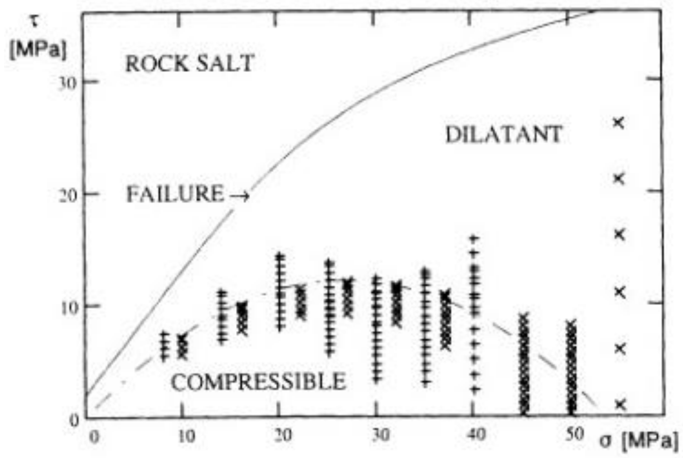


Figure 2-33 domain of compressibility /diltanacy experimental data (+++), models (xxx) (N.D. Cristescu et al., 1998)

The peak strength in the figure (2-34), has represented the short term failure boundary, which depend mainly on loading rate, and strain rate, if the rate will be increased, the peak strength increase too. However low strain rate and stress rate accompanying with constant load, the result will be ductile failure creep, on the other hand if the strain rate will be high, as well the stress rate, the brittle behaviour will be predominated.

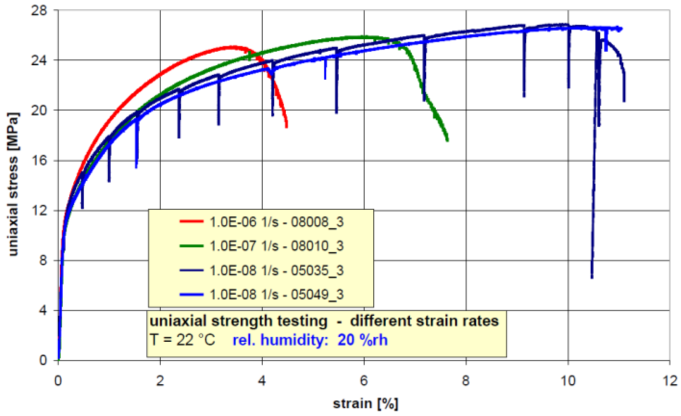


Figure 2-34 strain rate effect on behavior of rock salt (U. Hunsche et al,.2003).

The dilatancy boundary is important to detect a stable creep deformation without volume changes take place from dilatant deformation with micro-cracking and damage with failure, furthermore softening by humidity induced creep and then increase of porosity and permeability.

It was investigate two other boundaries which can be close to dilatancy boundary:

- Healing boundary (unloading).
- Damage boundary.

The area restricted between the healing and damage boundaries, is characterized by constant properties as volume change, permeability, micro-cracks, damage, seismic velocities, dilatancy and no healing. See figure (2-35)

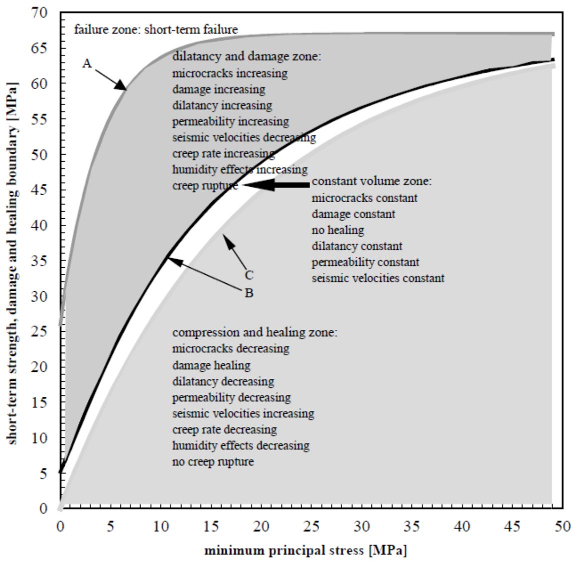


Figure 2-35 healing and damage boundaries of rock salt (Hou et al,.2003)

The healing boundary represents the upper limit of compaction zone, and during unloading processing, the strain rate will be associated with constant volume deformation, while below this limit, the compaction zone , there is healing process for damage (micro-cracking), if the micro-cracks have not be too large.

The dilatancy boundary accompanied with borehole instability of rock salt in deep wells, was investigated by Cristescu (Jin et al., 1998)

For instance to apply all these states, that rock salt might be skipped these limits ,when it will be loaded, see figure (2-36)which has shown different cases of oil wells with different depths.(Jin et al., 1998).

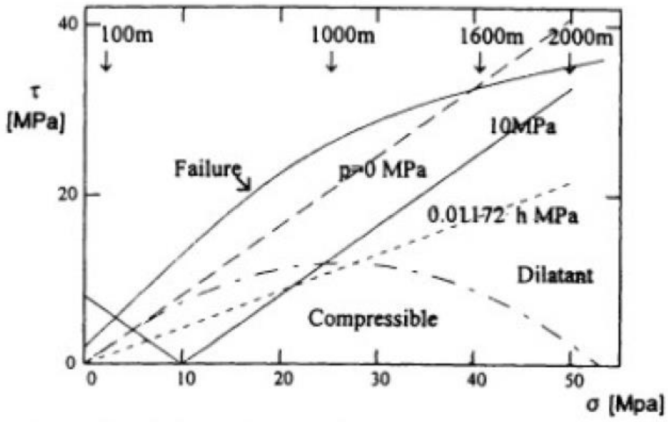


Figure 2-36 stresses on the wall of borehole of oil well for different cases and depths, it was assumed horizontal stresses are equal each other (Jin et al., 1998).

Actually the example which has shown in the figure (2-36), gives clear view how behave the rock salt with different depths and conditions, for instance, for depth more than 1600 Meter the wall of the well, will be under creep failure reaching to depth 2000Meter,while all working cases will be in dilatant zone. On the other hand, at depth 1000Meter and above, the borehole will be under creep in compressible zone and do not reach to failure while it will be exposed for dilatant circumstance (micro-fractures); the interesting example which connect with injection gas, the deeper borehole wall will be under dilatant, and if intermediate depth, the rock salt will be under compressible zone, farther shallow depth, return back to dilatant, even will be failure under tensile stress effecting.

The main constitutive equation that was done by Cristescu to evaluate borehole closure in excavation of borehole or caverns is:

$$\acute{\varepsilon} = \frac{\boldsymbol{\sigma}}{\mathbf{2G}} + \left(\frac{\mathbf{1}}{\mathbf{3K}} - \frac{\mathbf{1}}{\mathbf{2G}}\right)\boldsymbol{\sigma}\mathbf{1} + \mathbf{K_T}\left\langle \mathbf{1} - \frac{\mathbf{W(t)}}{\mathbf{H(H,\tau)}}\right\rangle \frac{\partial \mathbf{F}}{\partial \boldsymbol{\sigma}} + \mathbf{K_s}\frac{\partial \mathbf{S}}{\partial \boldsymbol{\sigma}} \ldots\ldots..(\mathbf{2-9})$$

It was analysed the stresses distribution around borehole with different depths and internal (supported) borehole pressures by using this constitutive models.

It was assumed also, the instantaneous (elastic) solution starting when start excavations the borehole, after that, the creep (the main part stationary) have been compliance with relaxation processing (the stress state will not be changed) to calculate the convergences of borehole with different conditions.

Most equations were derived for elastic solution and was added creep constitutive equations to investigate all stresses around borehole with different primary stresses cases. (Jin et al., 1998)

See figures (2-37).

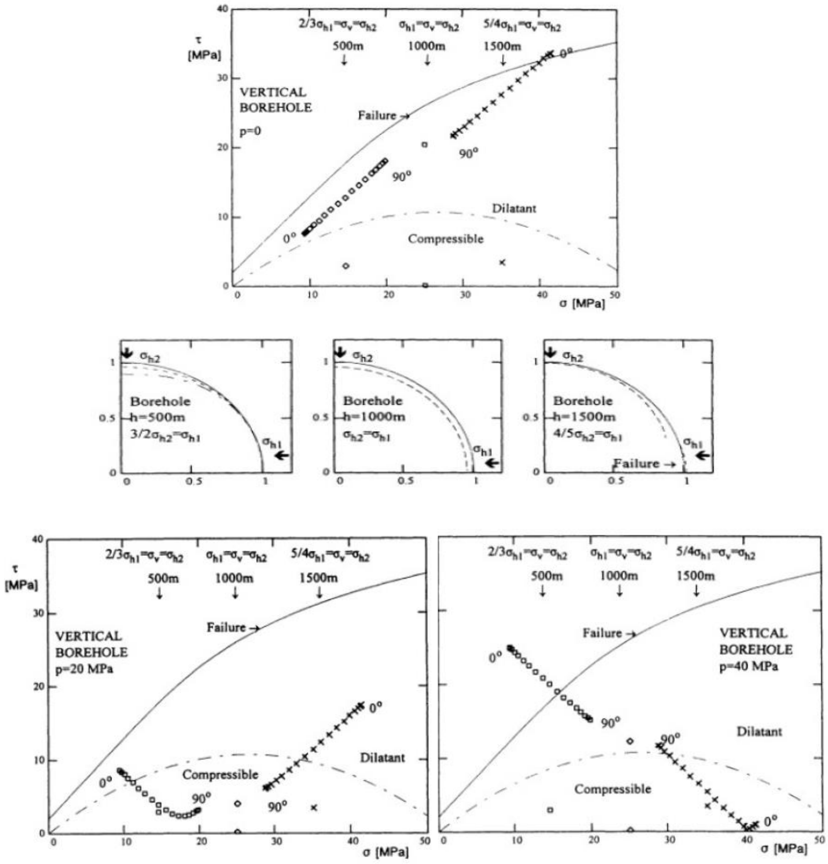


Figure 2-37 stresses distribution around different depths of borehole with different in situ conditions (upper), convergences of wall of borehole for the same example (middle), stresses distributions for supported boreholes (lower) (Jin et al., 1998)

The interesting point here, when an internal pressure would be increased to support the borehole wall from (20MPa) to (40MPa), it expected that, it will get stable condition for depth more than (1500 meter) , while under shallow depth this pressure do not support the borehole but it was considered the factor for unstable. On the other hand, the supported borehole by (20MPa), the borehole was stable for different depths, it can see clearly the stresses distribution around borehole (different theta angles) for different is situ conditions, while the unsupported borehole had been suffered by unstable condition especially for depth more than (1500 meter).

In order to see the accompanying relaxation processing with creeping, after instantaneous deformation due to excavations, the figure (2-38) has been shown that. The key point here, the stress state does not have changes, seeing through constant mean stress because the same value of primary stresses and secondary state.

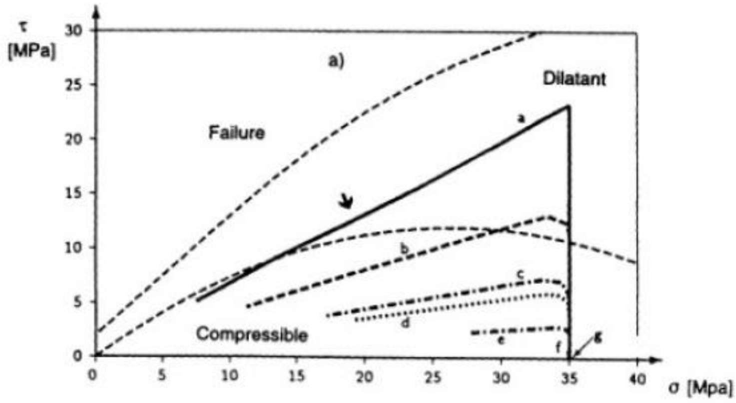


Figure 2-38 Stress relaxation during creep of the rock surrounding a deep shaft without internal pressure (Jin et al., 1998).

It depends on the conditions that have been surrounded excavations, sometimes; it was applied models just for stationary creep because it was thought the transient creep is not stayed too much after excavation, as well the value of disturb is not too much, because the drilling mud, most of time substitute the horizontal stress (Jin et al,. 1998). (.Dusseault et al,.2007).

So, its need powerful constitutive models that can cover the behaviour of rock salt, and most inelastic deformations are just creep, then all models that have been introducing, focus on the creep deformation which depend on stress state, temperature, grain size,…etc. Among, the models for rock salt but, here it was elected some of them for some comparison.

The constitutive law can be divided for three categories:

1. Physical model.
2. Rheological model
3. Empirical model

All of these models are found to describe the mechanical behaviour of rock salt.

2.3.2.3 The physical theory models

In contrast with empirical model, the physical theory model has been started from the microscopic structural of the material under loading, and generally is accompanied with a theoretical explanation of the time dependent behaviour.

It was started by metal and developed for rock mechanics' but with more complex than metal, because the metal is homogenous in its structural, while the rocks inhomogeneous.

There are amongst models which describe well the behaviour of rock salt, and it was selected three types of physical theory models, to give some outline of the most deformation of rock salt, which represent by creeps.

- Power law models (Norton-PL).
- Double Mechanism creep law model (DM).
- Multi-mechanism creep deformation. (MD).

The first model has been introduced as transient deformation, while the (DM) was established just for steady state creep and the transient was neglected. Despite the results that obtained by using (DM) is good compare with power law models, but it's still been suffered with some lag that coming from neglecting the transient creep. The best fit with experimental data model is (MD), which was based on both transient and steady state creep. See figure (2-39).

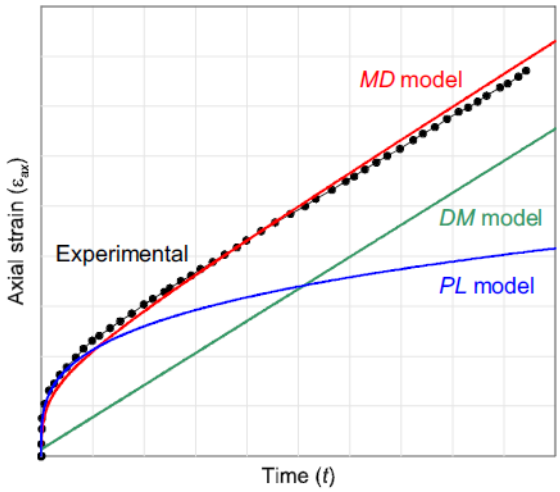


Figure 2-39 Comparison between three models (Firme et al,. 2016)

Also, the multi mechanics (MD) model has been considered the micro-mechanics processing that occur inside the lattice and crystal as (dislocation glide, dislocation climb, undefined processes).because it was evaluated the steady state creep for each processing. The mechanics map for dislocation processing can be created, in order to know the behaviour of rock salt at which process has being done.

Each models, consist of lot parameters which have to calibrate with different methods, physical interpretation of experimental data and mathematical fitting of the experimental curves. A numerical simulation is used to validate the parameter set.

2.3.2.4 Rheological models

Different rheological models which have used to describe the creep primary and secondary, most published papers have had agreed to describe the linear elastic part by spring, and the inelastic deformations that have taken different stages of deformation, as transient, steady stat and tertiary.

As well some part can go more to describe dilatancy and damage then failure, all of these stages can represent by dashpot and friction slide part.

A combination of these physical parts can describe the viscous behaviour on different deformation stages, using combination of electrical circuit rules for distribution the stress and strain which was created by this stress as the current, resistance and voltage, it can see part connect series while other parallel., as well the combination of these parts., the target to represent the behaviour, the linear part follow the Hooke’s law while a viscous element obeys the strain stress relation.

For instance the viscos-elastic behaviour might be used to describe a dry and saturated rocks, which represents by Burger model (consist of both Kelvin and Maxwell), this rheological model can represent elastic, transient and steady state creep.

However, these models can describe the mechanical behaviour of rock salt but it’s far from actual mechanism of deformation.

Different models have used extending from two elements simple linear viscoelastic model, to complicate for visoplastic model. Despite the rheological models are sophisticated generally to describe the infinitesimal strains, but it cannot associated the thermal effect with deformation. Also, the rheological model is restricted with small range of stresses too, despite the boundary conditions of rock salt has been extended for various and wide circumstances. The famous rheological models that are used to cover:

- Linear viscoelastic.
- Non-linear viscoelastic.
- Elastic viscoplastic.
- Viscealstic plastic.
- Viscoelastic viscoplastic.

The linear viscoelastic models have been covered by:

- Maxwell model (ealsto-viscous).
- Kelvin model.
- Generalized Kelvin model.
- Zener model.
- Burger (Maxwell-Kelvin).

Each model can be used to describe stress state, and it can be fit for it, for instance the experiments that were fit the linear viscoelastic models (Gangi et al,. 1981), the steady state creep was covered by Burger model consist of, Zener model which cover transient creep and Maxwell model for steady state creep. See figure (2-40).

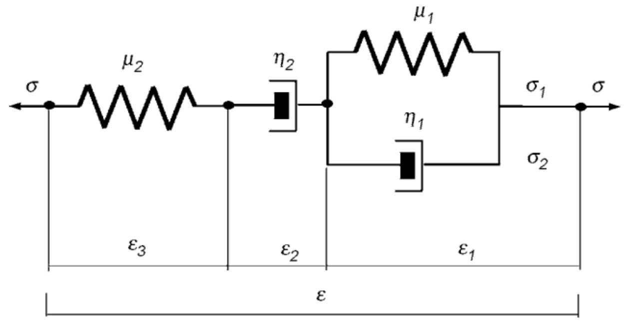


Figure 2-40 Burger linear viscoelastic model (Carcione et al,. 2006)

The example which was used linear viscoelastic (Maxwell, Burger) models has been shown in figure (2-41) (Carcione et al,.2006) which was calculated for two cases when (σ_h =0, 9*σ_H, σ_v =σ_H , P =0, 9*σ_H), and the depth for oil well in this example (4000 meters).

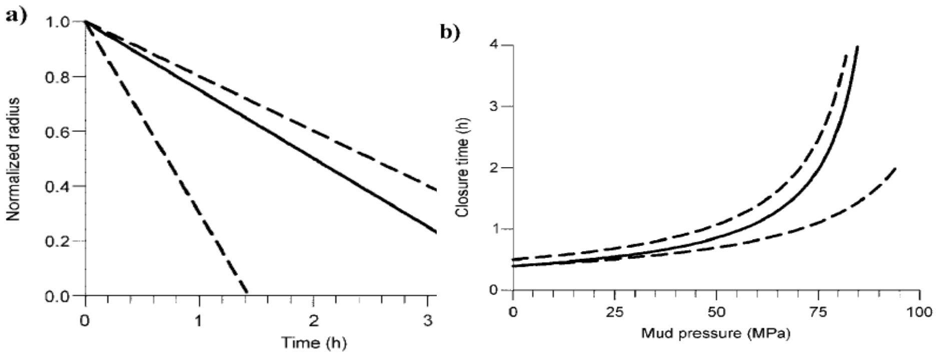


Figure 2-41 left) changing in elliptical axis's (dashed line), circular shape (solid line) vs. time. (right),closure time (hr) vs. borehole pressure(elliptical) dashed line, circular (solid line). (Carcione et al,. 2006)

It has shown that using Maxwell model sufficiently covers the creep behaviour of rock salt in borehole of oil well, the viscosity (steady state creep) is not Newtonian and depended on the temperature (Dusseault et al ,.2007), while the Young modulus was assumed constant., however this assumption might be bearing inaccurate predication for other type of rock as sandstone, because when the confining pressure will be changed for any reason, the elasticity modulus should be changed, it was approved (Santarelli et al,.1986)

See figure(2-42) left, as it can see, while in rock salt ,it's seemed this assumption is realistic , because when confining pressure increase ,it cannot see big change in the linear part of curves, when the confining pressure was being changed (see figure right)(Senseny et al,.1992)

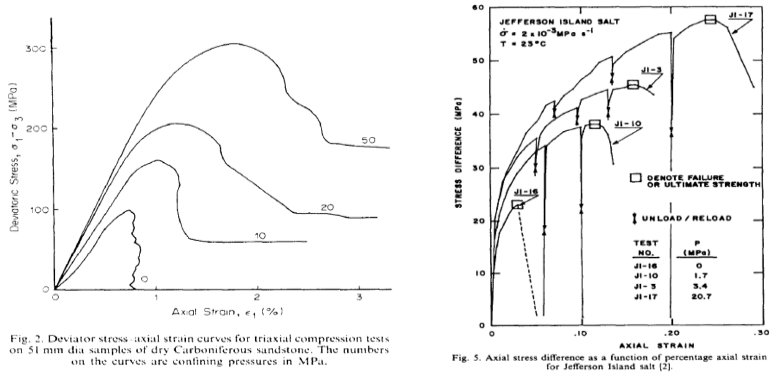


Figure 2-42 comparison of elastic modulus vs. confining pressure between sandstone (left) and rock salt (right)

2.3.2.5 Empirical model

The empirical models are arbitrary functions formulated to fit set experimental results; here the actual mechanism was ignored, as the rheology model. The empirical models have been taken different mathematical relations (power, exponential, polynomial…etc.).

The development was done of the empirical constitutive law to connect the creep strain, stress, and temperature together. The solution can be obtained from empirical equation by using strain- hardening or time –hardening and viscoplasticity flow rule. The potential law for instance is power equation related to strain, stress, time, and temperature, the elastic part of these equations, classical way to calculated by using elasticity theory, while two empirical equations which use for transient and steady state creeps

$\boldsymbol{\varepsilon}(\mathbf{t}) = \mathbf{k\sigma^{\beta} t^{\gamma} T^{\alpha}} \dots\dots\dots (\mathbf{2-10})$ (transient).

$\acute{\varepsilon}(\mathbf{t}) = \mathbf{A\sigma^{B} T^{C}} \dots\dots\dots\dots. (\mathbf{2-11})$ (Steady- state)

Where **ε (t)** = transient creep strain

$\acute{\varepsilon}$ (t) =steady –state creep strain rate

σ =stress

t=time

T=Absolut temperature**,** **K, α, β, γ, A, B and C** = material constants.

These empirical equations can be used to simulate tri-axial tests and field data. However these equations are not physical because it was collected all phenomena in one term, and there is some processing which are being happened in rock salt that is not concluding, and should be modeled as macroscopic creep, which is considered as a function of constitutive behaviour combined with geometry and stress changes.

(Empirical equations based on such data cannot lead to a physically correct constitutive law because macroscopic creep is a function of constitutive behaviour combined with geometry and stress changes. It is now clear that these must be treated separately and correctly, using continuum mechanics approaches) (.Fredrich et al,.2002).

So, a good predication law which draw the good capture the behaviour of rock salt, especially when is support by extracting a core.

However, this step are very difficult because the cost and other concerned difficulties, deep bed salts (more than 2800 m depth) which is accompanied with active tectonic area, which effect directly on salts.

Also, the good models that will take the effect of drilling mud mechanically, chemically and hydraulically as well temperature. Most constitutive models have been taken a creep of rock salt as based to calculate deformation of rock salt under some circumstance (wide range of variables effect in every case), stress (difference between overburden and hydrostatic pressure of the drilling mud).(Backers et al 2013),as well the temperature range for oil well drilling are wide range (30 C-120C) and humidity for instance, as mention before, the lattice of one crystal of rock salt will be deformed, by different type of micromechanics mechanics (dislocation glide, cross slip, and climb)., so the good predication that is covered all types of deformation (micro and macro)(transient , steady state and tertiary as well residual strength), for that reason the rock salt have been covered with lots of models which has been trying to discover every variable which play role in deformation processing .

2.3.3. Flowing of salt

Most researchers whom have been discovered the rock salt creep, describe behaviour of rock salt as viscoplastic ,while some other consider viscoelastic (on tectonic time scale 10^0-10^8 years , deforms by crystalline solid –state creep) (The rock salt behaves as elastoplastic for short time , and the general behave that faces in drilling operations , responds elastically front of a drill bit, and it has been taken period (10^0 -10^3 hours) to dissipate the elastic stresses by viscous creep, which can be evaluated by using Maxwell model. The creep of rock salt depends mainly on viscosity, which has been affected by other important factors, as moisture, temperature, and grain size as well strain rate.

The range of this viscosity extend between (10^{16}-10^{19} Pa.s) , however there is viscosity less this range for instance 10^{15} Pa. s (Weijermars. et al,. 2013), as well it was mentioned the closure rate 10^{-8} s^{-1} for this viscosity, as well their study was based on Young modulus 3 GPa , which was taken for pure Mogilno salt (Gryzybowski et al .2008) , the interesting results here, that 7% just is relaxed as viscous creep from the initial elastic stress into well bore after 100days for viscosity of rock salt 10^{16} while 1000days for viscosity 10^{17} , furthermore 27 years for 10^{19} , and if the Young modulus will be more than 3 GPa , by 10 factor which decrease the time for dissipation, and the surrounding rock salt around the borehole subjects both elastic stress and creep viscous stresses due to tectonic and flowing rock salt sheets. Rock salt consider the source of perturbation of stress and its direction of principles stresses on wall of borehole and will create more complex borehole instability.

The new idea here which was introduced by Weijermars, depends on sink flow inside the borehole location in the wide sheets flow of rock salt, which was driven by gravity forces, represent by overburden rocks weights. However, most studies which described crystalline creep of the rock salt, is not taken in account the effect of far field salt creep.

The interaction between a far field uniform flow and sink flow inside borehole as result of superposing, and it was represented by stream function. The borehole closure is controlled by sink flow strength (m) that drives by overburden load and tectonic far field salt creep rate (U_∞)

The ratio between those ($|m/U_\infty|$) reflects whether the borehole closure will be strong if the ratio is bigger than 1, and the stagnation point will be far from borehole , however if this ratio less than 1 or 0 , the Rankine flow will be less effect. See figure (2-43).

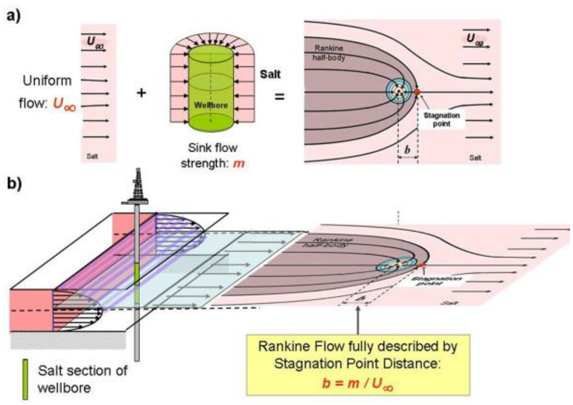


Figure 2-43 a)Rankine half-body sink flow, b) cross section for salt flow in oil well(Weijermars et al 2014)

The most three important equation which was used to calculate borehole closure depending on the Rankine flow as follow:

$$a(t)/a(0) = (1 - t\,\dot{e}xx)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2\text{-}12)$$

$$\dot{e}xx = -(U\infty)_{r=a}/a0 = [(\rho_{MEAN} \times g \times d) - P_{NET}]/2\eta\ldots.... (2\text{-}13)$$

$$m(t) = -\{2\pi[a(t)]2[(\rho_{MEAN} \times g \times d) - P_{NET}]/2\eta\}\ldots..\ldots..(2\text{-}14)$$

Here by applying these three equations in one of Iraqi case study, that the rock salt was loaded bad cemented casing pipes ,and it had taken defect by reducing inside diameter by value (40 mm)through (53) days. See figure (2-44).

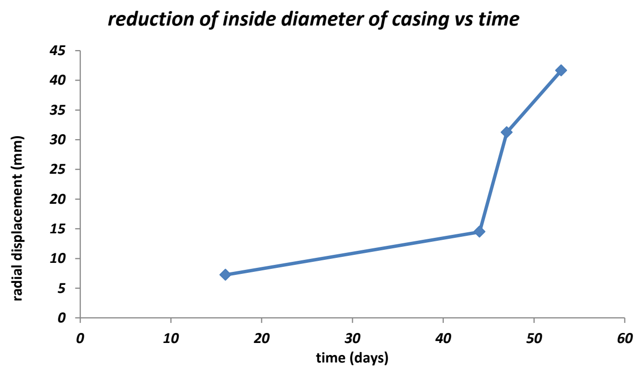


Figure 2-44 reduction of inside diameter of collapsed casing pipe by salt loading for one of Iraq case study

The figure has shown during the 35 days the reduction was gradually, but after this period the reduction steeply increasing, may be because strength of steel pipe was decreased too much, and reached completely failure.

The equation above which was used to calculate the viscosity of Iraqi rock salt by applying the closure rate from the case study, overburden stress, the viscosity is 10^{14} Pa.s., furthermore if it is used the typical far filed uniform flow rate which is (3.17E-11 m.s^{-1}) , it was found the initial stagnation distance equal (1340 m), which shows the dominate of the Rankine flow approved by low viscosity

The Couette-Posieuille number was introduced by Weijermars, to estimate the lateral shear stress, which is loaded the casing pipes by salt layer. The range of viscosity that was assumed for rock salt between (10^{15}–10^{19} Pa s), that is came by creep of rock salt with rate approximately (0–10 mm yr.–1), and calculated the produced drag force on rigid casing steel pipes, the drag force reach sometime to (1000MPa) (Weijermars. et al,. 2014), so, it was considered, there are a thick flow between sheet layers of rock salt under the load of gravity.

There are two flow laws which are used to characterise flow behaviour in rock salt, one for open borehole (Rankine flow) and the other (the Stock law) describes the drag forces on the casing pipe for a cased borehole.

A boundary conditions, detects which law should be used, if the rock salt located between two fixed layers of rocks, here Poisieuille flow will be used and the gravity pressure drives the rock salt for its movement.

However, if the rock salt ,was not move from one side (velocity profile),and shear stresses will work under constant value along the rock salt, here Couette flow can describe it, sometime both of them can be used.

Despite the rock salt behave most of time, as viscos-plastic material , and other time, as viscoelastic but it is assumed, it has constant viscosity (Newtonian), for the range of viscosities mention above, the time for decaying elastic stress extended from 10-100000 days by using Maxwell model. For rock salt (3 GPa Young modulus)

It was introduced dimensionless number which was represented the ratio between Couette flow and Poisieuille flow (CP). .If the CP equal to zero, meaning just Poisieuille, however Couette flow detect ,when CP is going to infinity in negative and positive values.

This number can describe well a direction flow of salt which effect directly on borehole (covered with casing pipes or not covered) because, as the study was mentioned, the rock salt sheet move in contrast way of Poisieuille flow, when CP less than zero, while move at the same way of Posiieuille flow, when CP more than zero, the other important point also, that is related to the neutral point when the shear stresses change their direction.

It was summarized, to calculate the Couette flow in two equations, one of them depend on the overburden displacement rate of rock salt, (U_{XTop}) as well, the effective viscosity and bed thickness of rock salt , but the most important effecting factor here, is the effective viscosity, which was taken, as mention between (10^{15}-10^{19} Pa.s), this range was taken to be far from arguments about the type of viscosity (Newtonian or non-Newtonian), which depending directly on strain rate, grain size, and moisture, as well less effect of temperature.

- $\mathbf{T_{XY\ Couette} = (U_{X\ TOP}/2h)\eta}$ **……(2-15)**

The other equation is used, when the rock salt sheets were deposited by angle from the horizontal plane. The overburden pressure here effect and drive the rock salt sheets.

- $\mathbf{T_{XY\ Couette} = \rho_{OVERBURDEN} g H \sin \alpha}$ **……(2-16)**

In addion , the previous two equations, there were other equations that give way to evaluate the flowing of salt sheets, maximum shear stresses which is equal to the sum of the effect of the Poisielle flow and Couette flow , as well CP. The key point which detect the type of flow effecting on rock salt,is the relation between the thickness of rock salt compare with thickness of overburden formations. If (H/h)>>0 and the thickness length ratio (L/h)>>0, which is meant, long thin section of rock (Iraqi salt case study), the Couette flow is dominated. However, some Iraqi case studies have thickness of rock salt reach to (80 meter), as well big thickness of overburden formations, so it will be less than two types of flows (Piesielle and Couette) by using equation

$T_{XY\ Couette} / T_{XY\ poisielle} = (\rho_{OVERBURDEN} / \rho_{salt})*(H/h) = CP$ …..(2-17)

It will get CP = 524 for Iraqi case study, which clearly show the effect of the Couette flow.

All these equations can give us view of salt sheets flow, and introduce to dragging viscous forces on the casing pipes for vertical borehole. These forces effects directly on two points, anchored of the casing when enter the rock salt and, when it will exit., as well, the far field velocity which depend on the depth of rock salt, as the CP are very large for Iraqi rock salt (case study), the velocity will be high on the top of rock salt, and along section of casing hole, the velocity was considered (1/2 U_{max}) for pure the Couette flow , and for pure the Poisielle flow (23 U_{max}), while for (0<CP<infinity), the range between (3/6-4/6)U_{max}. Also, a laminar flow for high viscous rock salt flow, was assumed, which was creating drag force around very rigid casing pipes on rock salt. Two equations can summarized the drag force on casing, one to calculate the drag of coefficient of laminar flow, and other for drag force, as follow.

- **$C_d = 4\pi / (\log (L_c/a) + 0.5)$ …….(2-18)**
- **$F_d/L_c = C_d\ \eta\ U_\infty$ ………………(2-19)**

For Iraqi case study, the C_d equal 6.212 because the length of rock salt bed equal to 5 metre compare with radius of hole 0.155 meter, and if it was assumed the typical far field velocity equal to 10 mm/year, then U_{max} for Couette flow will be in range between (3/6-4/6) of U_{max}, so it will get 6.6 mm/year, and if effective viscosity 10^{-14} Pa s, so the drag on casing will be 0.65 MN

It was expected that, because the viscosity low, if the viscosity increased to 10^{16}, it will get 65 MPa, but when the viscosity equal to 10^{17} the drag force will be 650 MPa, the casing will be failure.

It can see this relation from the figure (2-45) which was done by (R.Weijermars. et al,. 2014).

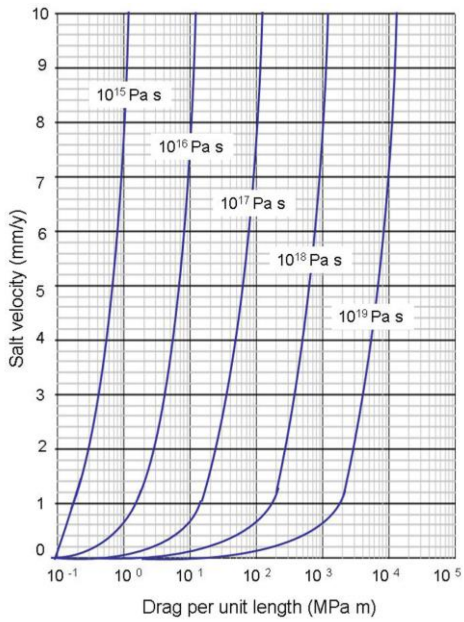


Figure 2-45 Drag force vs. salt velocity (Weijermars. et al,. 2014)

The far field velocity (viscous creep) will be less when viscosity increased of course.

2.3.4. Casing pipes and creep of salt

Casing collapse has been considered a big challenge for drilling operation of oil and gas wells, because this event was classified as non-productive time, and it add as additional cost to mitigate without any drilling progress. Different types of rocks can be responsible to create this problem, as shale, marl and rock salt, but some published papers have been named the rock salt behind this problem.

Different types of salt loading on the casing pipe, and lots of papers that have been introduced this issues (.Dusseault et.al,.1998)(Zhao et al,. 2011)(Lin et al ,. 2014)(Salhei et al,.2009)(Sun et al,. 2012)(Lao ,. 2012))(Ge et al,.2011)(Zhu et al,.2013)(Wang et al,. 2012)(Poiate et al ,. 2006)(Zhang et al,. 2008)(Pfeifle et al,.2001).

Generally, the normal practice, which is used in drilling operations, covers the borehole by stiff pipes and then support by good cement.

That does not mean, the cased borehole will be far from the problem, because, the cementing operation is another challenging for the borehole, the challenging have been came from the irregular borehole shape, due to washing in borehole because the salt beds, or sloughing shale .The drilling muds have been tended for washing salt at the bottom, because the temperature which will effect on solubility of salt.

The other type of rocks which will inter-bedded with rock salt, as shale, that might be tended to slough (pressure heaving shale). This sloughing will be inside the borehole wall, and then will be extended, or it might be, aggravate to stick a string pipes.

In brief, the cementing operations will not be easy; because it might be given the problem of casing pipes collapse more complexity. The sedimentary rocks as rock salt are considered big risk for the casing pipes, because the non-uniform loading.

On the other hand, part of published papers have shown, it can use, casing pipes without any cementing operation opposite the plastic rocks, to be sure that the casing pipes will be uniformly loaded, but for regular borehole (Willlson et al,.2002).

However, the cementing operation for irregular borehole is very important, because the cement have the ability to convert the non-uniform loading to uniform. The relation between three keys of the problem (salt, casing and cement) was assessed very well by using new apparatus which was designed to study effecting three important players in oil well, by Sandia National Laboratory (Pfeifle et al,.2001).

The movement of rock salt toward the borehole is controlled by geological structural of rock salt itself, for instance if there are sub-salt reservoirs, of course these reservoirs will be produced , the compaction which will be initiated by production of oil or gas, will lead to create horizontal stresses, that the rock salt response by creating bowels. See figure (2-46).These bowels are responsible for anisotropic loading on the casing strings, which will be led for collapsing the casing in one stage from the creep behaviour of rock salt.

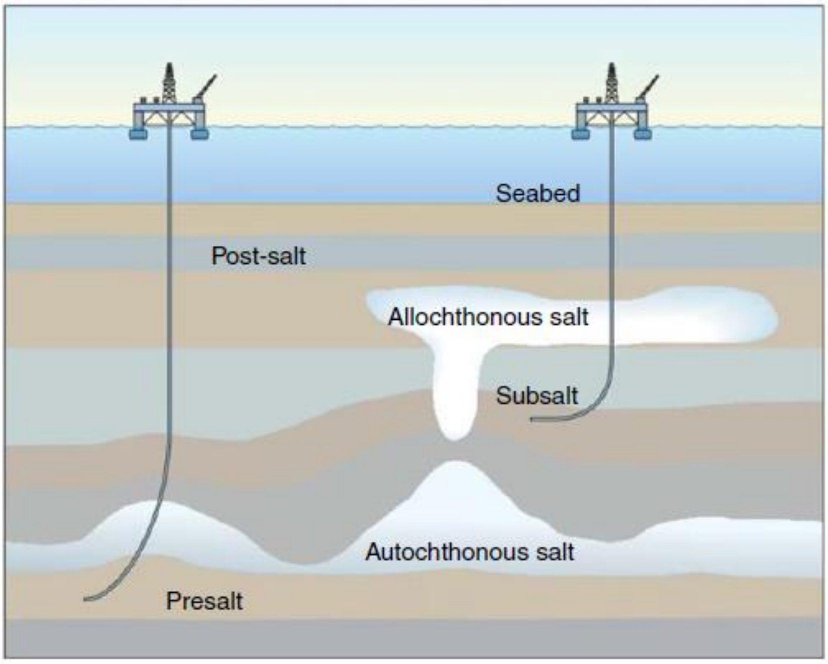


Figure 2-46 subsalt and pre-salt reservoirs (Wang et al,.2016).

The big risk on the casing in a borehole, when rock salt is there, because it can be loaded the casing in one point, which is called the point load (loading over a limited contact arc). It might be happened, when interface between salt with other rocks, especially when the casing is not centric inside the borehole. Creep of salt (borehole closure) means that point loads can be generated, and this is the most dangerous condition to impairment the casing pipes.

Sometimes, this issue can be solved by good design of the mixed casing string (using heavy weight and lightweight in different sections), furthermore, a good cementing operation, meaning create good cement sheathe of cement will help the load to be uniformly on the casing rather than point loads (collapse the casing).

in addition, there are other pattern for collapsing the casing pipes, its shearing effect by hard rock as anhydrite, furthermore the potential of that shearing might be came by rock salt movement.

There are other factors contribute to create this problem, as rotate of a drilling string inside deviated borehole that will be led to mechanically wear of the casing pipes ,then reduction the ability of casing to withstand outer stresses that come from plastic zone as the rock salt or a drilling in active tectonic area.

It was thought this problem, connected with a bad quality of pipe, that's not correct, because the drilling operation has been designed to use high quality equipment's and tools to reduce the cost from side and gives the safety and security in the first rank. The problem is appeared because sometimes it has not been taken all variables which effect directly on behaviour of some plastic rock.

Most of time the circular shape was assumed for borehole, from geometrical point of view., its true if this borehole contain just from one type of rocks, but the tectonic forces ,and sedimentation circumstance which create strati-graphically sequence of different rocks. Generally, oil or gas borehole should be reach to its target "oil and gas reservoirs", which has been usually as anticline or accumulations between lots of fractures and faults.

So there are inter-bedded between different ages of rocks, which lead to irregular borehole geometry, furthermore, anisotropic stress distribution, specially maximum and minimum horizontal stress, all of these lead to get elliptical borehole or irregular shape.

Most oil wells have a harsh condition, which need a good design and manufacturing of steel casing pipes. The casing pipes in general, consists of two important parts, connection (thread) and the body, which has been manufactured to withstand the robust conditions of high temperature high pressure oil and gas well. Most of the cases studies under this thesis here, the failure were in the body rather than the connection thread. (Staelens et al,. 2012)

The seal of thread under hard test condition is the criteria for failure function and might be tested by using numerical method, but of course only the full set of laboratory tests that can quantify the ability of sealing of the thread of casing pipes. So, in order to cover all demands for oil industry from tubular parts for drilling and completion uses, API 5C3 was presented to cover collapse pressure, burst pressure and joint strength (thread connection) but collapse pressure are focal point here, so collapse pressure with no internal burst pressure and axial load, can be convert to ratio of diameter to thickness of pipe, and minimum yield strength of pipe body.

So, it was divided the collapse area into four regions depending on ratio between outside diameters to thickness.

This ratio are depended on steel grade, so equation that is used here to evaluate collapse pressure ,actually its' Lame thick wall solution , which convert the external pressure to tangent stress that overcome the yield stress as equation below, which is work for D/t range <11-16 (thick wall)

$$\mathbf{P_{Y_P}} = \mathbf{2Y_p}\left[\frac{(\mathbf{D}/\mathbf{t})-\mathbf{1}}{(\mathbf{D}/\mathbf{t})^2}\right] \ldots\ldots (\mathbf{2-20})$$

The other option when increase the ration(D/t), here the pipe casing will be under control plastic region, the equation that describe this area is empirical and was extracted from more than 2488 tests, (A,B and C) are regression constants for curve fitting , which are actually depended on the grade of steel pipe.

$$\mathbf{P_P} = \mathbf{Y_P}\left[\frac{\mathbf{A}}{(\mathbf{D}/\mathbf{t})} - \mathbf{B}\right] - \mathbf{C} \ldots (\mathbf{2-21})$$

The third area where pipes state will be in transition between plastic to elastic zones, which can describe also with the following equation (the (F and G curve fitting factor depend on steel grade)

$$\mathbf{P_T} = \mathbf{Y_P}\left[\frac{\mathbf{F}}{(\mathbf{D}/\mathbf{t})} - \mathbf{G}\right] \ldots\ldots (\mathbf{2-22})$$

The fourth area which the ratio of D/t will greater than (20-40), meaning thin wall pipe, this area is called elastic zone, which the pipe will be independent of yield strength, and the formula below describe this mode

$$\boldsymbol{P_E} = \frac{\mathbf{46.95*10^6}}{(\boldsymbol{D/t})[(\boldsymbol{D/t})-\mathbf{1}]^2} \ldots\ldots\mathbf{(2\text{-}23)}$$

See figure (2-47).

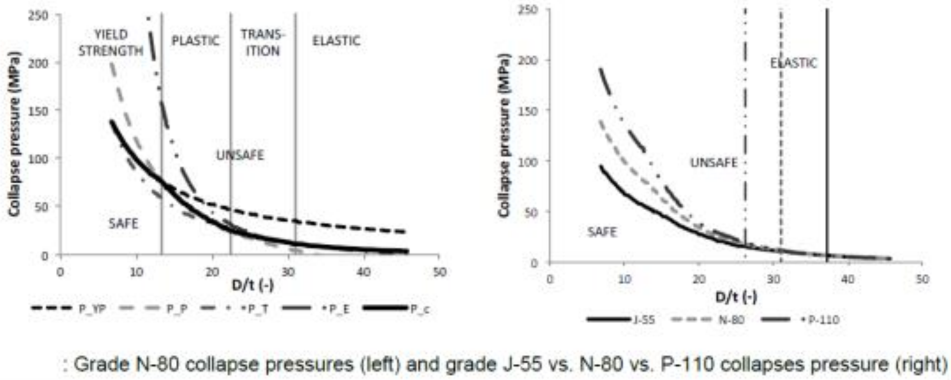


Figure 2-47 fourth collapse pressure zones vs. D/t (Staelens et al,. 2012)

So, it can see from the figure, the safe zone, it will be far from plastic zone, and near from yield strength by effecting of ratio (D/t), for the same grade (N 80, it was elected as example) (left figure), and when the ratio increase (thine wall casing), it will put the casing pipe in unsafe zone, that it will happen ,when wearing inside the casing pipe by mechanical action of drill string, (deviated borehole).

It can see also, (right figure), when the casing will be high grade (high yield strength), it will be more safe than the lower grade, however the increasing of the grade of pipe will decrease the resistance from mechanical effect (rotate drill string), it can see, for ratio (D/t =10), it can reach to withstand collapse pressure for grade (J55) to 70 MPa, while for the same ratio is 150MPa.

Sometimes, indirect reason might be considered the main reason of collapse as:

- Wearing casing by drilling practice due to high deviated hole and without a good plan (decreasing the thickness) .See figure (2-44).
- Bad cementing operation complaining with other circumstances that lead to buckling of casing, and then wearing (decreasing the thickness) .See figure (2-48).

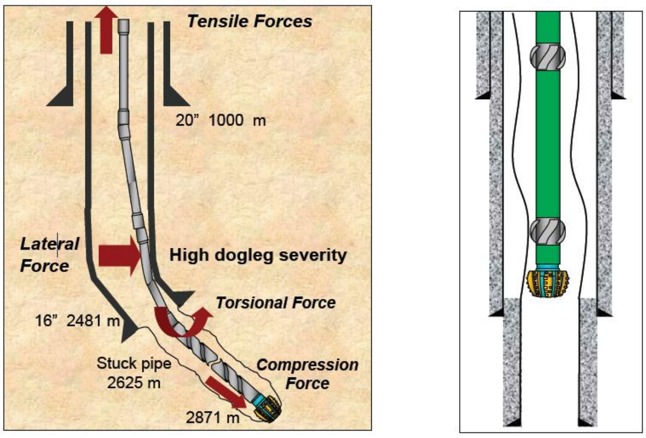


Figure 2-48 pipe casing wear due to dog leg and buckling issues(Asadi et al,. 2011)

Furthermore, different papers which was published and that have been shown the collapse casing mechanism, in different area. (SAlehi et al,. 2007)(Asadi et al,.2011)(Ashtiani et al,.2010).

Mechanism of shear casing

The mechanism of shear casing is important phenomena in the oil industry that it might be happened when the casing close to formation, which can be suffered by deformation along bedding plan (difference in stiffness's) or steeply inclined fault planes. This displacement can cause shear failure, because a differential stress was concentrated in this zone with help of other factors as temperature for instance. There are many factors which contribute to create this displacements as changing (in volume, pressure, temperature and solid movements) that has been came from operations take place in oil well or borehole as (production or injection).

The best place that this displacement prefer is bedding plane (interfaces between two different types of rocks , joints, faults) , when the stresses(overburden stress) play directly on these interfaces, which will create horizontal shear stress on these planes that overcome the material rock strength which force them for movement by effecting of active tectonic area.

Sometime, the reservoir rocks locates near to casing pipes setting , and this setting place will be near to active bedding interface ,as between anhydrite and rock salt.

A production or injection from these pay zones, will make changes in stress distributions which in the end leading to create displacement, effecting on both casing and closest inter-bedded interface.

Even, if this casing pipe will have good cemented, this sheathe of cement is not support the shear stress because it is bigger than strength of cement, but it help to support the casing a while of time, or trying to distributed the stresses if the casing do not have any buckled. (Dusseault et al,.1998)

It can be avoid these shearing stresses by using high grade of casing with high weight to be able to withstand, or using a good drilling operation when it was detected exactly by expanded the hole opposite of these zone, in order to create safe distance or put the casing as far as from these zones, but this technique will not work well, if one of these zones consist of plastic rocks as rock salt.

Most of oil fields in the world, the reservoirs consisted of anticline, while the other are created by trapped between different types of faults. All the Iraqi cases studies where the folded production reservoirs closest to the casing setting, however part of the wells was drilled near to shoulder and other to flank ,these places are very dangerous because shear induced stresses which give lateral displacements for the weakest bedding plane, due to production from the closest reservoirs. This production introduces a compaction of the reservoirs' rocks, which lead to increase the thrust fault type on the crest (the horizontal stresses becoming the main principle stress), while in the flank, the overburden stress intense through normal fault type.

Furthermore, other wells may be suffered from this case even they are far from production zone, because the complexity of deposition , which was put porous rock as shale inter-bedded with rock salt, and because the drilling operations gives the shale chance to produce content water, even with low rate. This production of content water creates lateral induced shear in the interface acting on the casing pipes, as it will see in the Iraqi case studies.

If the plastic formation strata have significant thickness, the shear lateral stress will be less compare with small thickness, in the latter case, even using thick wall pipes casing will not support, but it will decrease the effect. See figure (2-49).

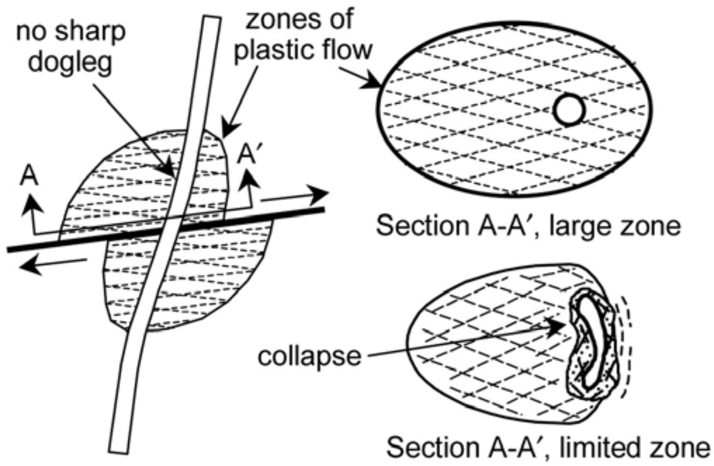


Figure 2-49 Plastic formation flow around casing. (Dusseault et al,.1998)

Chapter 3: Geology of selected case studies

3.1. Italian rock salt

The salt deposits in the worldwide extend through the range of the geological ages (Permian, Cretaceous, Silurian, Devonian, and late Miocene), and distribute between marine and continental environments.

The greatest volume of salts is in continental tectonics basins located in the world desert belts, as well, the late Miocene Mediterranean evaporated show the greatest extent also. These evaporated extent between CA-sulphates and halite which deposited at the end of Messinian stage. See figure (3-1).

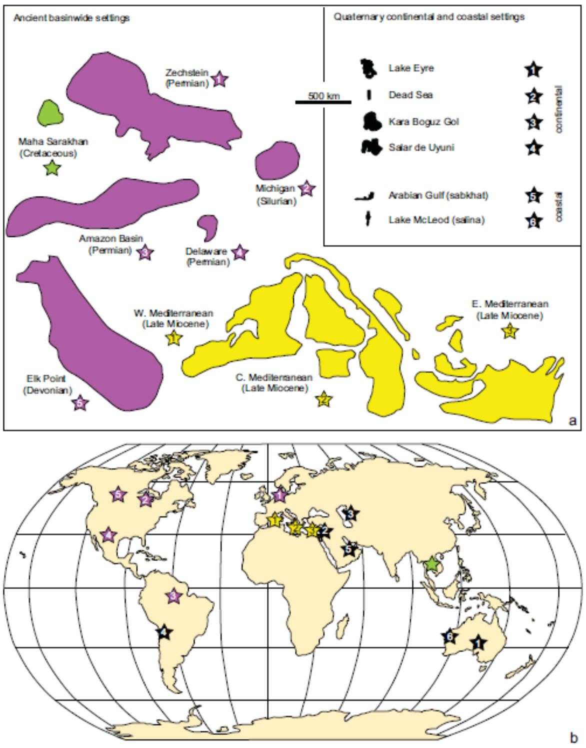


Figure 3-1 salt deposits through different geological ages in worldwide

3.1.1. Messinian evaporates

One of the most important evaporate event was occurred when the connection and exchange between Atlantic Ocean and Mediterranean Sea was restricted, which had led a fully marine evaporative environment.

Actually, the area that has been considered the host of the Messinian evaporates (Gypsum and halite) locates at Italian Peninsula. This Messinian evaporates was classified According to their importance into three basins: the Volterra (Tuscany), the Crotone (Calabria), and the Caltanissetta (Sicily) basins.

1. **The Volterra basin**

The Volterra basin consists of a sedimentary succession extending from late Tortonian to Pliocene that represents the upper part of the Messinian evaporation succession (alternating gypsum, conglomerates, sandstone, clay stone and halite). Here the halite will be inter-bedded with different rocks as anhydrite, sandstone, and clay, and constitute 40 % from the total volume which has have nearly 200 meter thickness. This basin is characterized by moderating the bend, and less diapiric movements.

The Volterra basin had been suffered by high heat flow and hydrothermal fluid circulation since the late Miocene due to the several magmatic bodies which collisional and involved the southern Tuscany and northern Tyrrhenian basins.

2. **The Crotone Basin**

The Crotone Basin is a forearc basin in central Calabria; it was classified as Neogene evolution which is related to the Calabrian Arc and rollback of the Calabrian subduction zone since Serravallian time. The period between the serravallian to Pleistocene has been occurred three sedimentary cycles which created conglomerates, sandstone, claystone deposits and the Messinian evaporitic interval (gypsum, breccia, claystone, sandstone, conglomerates, and halite). The halite deposits thickness is changeable reach to 200meter, as well crops out in the north part of this basin.

3. The Caltanissetta basin

The Caltanissetta basin which was extended north east to south west, the stresses part locates in the south western of Sicily. This stresses part has complexity syncline structure for period extended through the Tortonian, and the sediments fill the basin, the halite locate in the upper evaporites , that separated by a basin scale erosional surface(the Messinian Erosional Surface, MES). Chalk and conglomerates fill the basin, and the halite deposits had been occurred as independent bodies with thickness reach to 500 Meter , and wide for more than 20 Km. The most of three mines which including of this basin are, Petralia Sottana, Realmonte and Racalmuto. See figure (3-2).

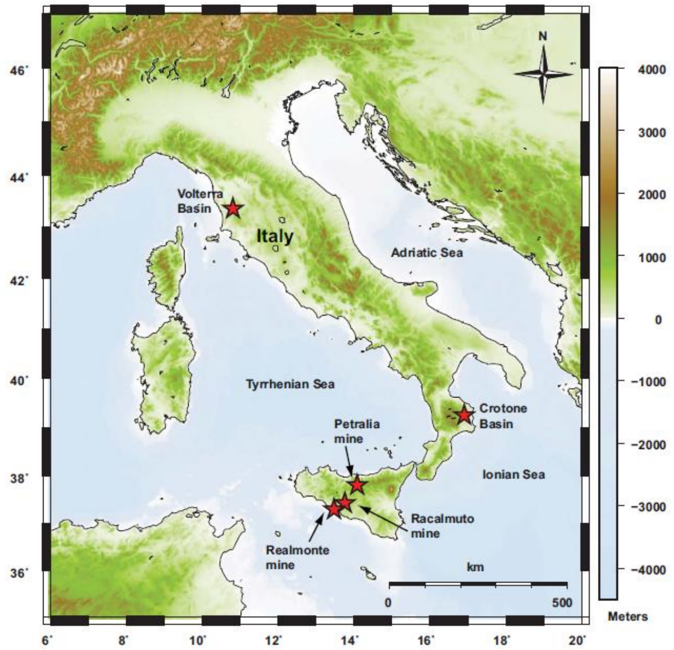


Figure 3-2 rock salt basins, and mines for The Caltanissetta basin (Speranza et al,. 2013)

3.1.1.1 The Caltanissetta basin mines

- **The Realmonte mine**

The Realmonte and Racalmuto mines locate in the province of Agrigento, while Petralia mine locates in province of Palermo, managed by the company Italkali, however all mines locate in Caltanissetta basin ,The Realmonte field overlooks on the southern coast of Sicily, about 4^{th} km from Agrigento and 1 Km from Porto Empedocles', Italy.

It consists of a vast saline lens, aligned according to the coast, which runs between Porto Empedocle and Siculiana. The layers of rock salt and kainite dive on a regular basis from the mountain to the sea, with rock salt stratification roof of kainite and with an output of up 40 meters and title in sodium chloride between (97 - 98) % reserves have been established for about 100 million tonnes of rock salt and confirmed the presence of significant amount of potassium minerals that have been developed programs for industrial exploitation.

The thickness of rock salt in Messinian Realmonte deposits extended between (400-600) meters, which were divided into four parts or units from bottom:

- Unite A laminated gray halite with white anhydrite nodules and laminae passing upward to gray massive halite beds.
- Unite B, massive layers of gray halite inter-bedded with light gray thin kainite , also the upper part of this unite contains thin layers of gray kainite layers near the top of Unite C , the kainite zone is replaced by an halite –anhydrite-mudstone dissolution breccia up to (10-30) cm., the total thickness of this unite is about (100) meter
- Unite C, white halite layers (10-20) cm thick separated by irregular dark gray mud laminae which contain small amount of light gray poly-halite and anhydrite ,it has thickness (70-80)meters ,and it was missed in the south and south west of the deposit.
- Unite D, composite from (15-20) meter thickness of anhydrite gray mudstone which were passed on laminate followed by gray halite which have thickness extended between a few millimetres to centimetres , this unite in the south and south west was missed too.(Lugli et al ,.1999)

These unite can be seen in the figure (3-3) (left). The Realmonte salt deposit is complicated because intense folding was happened, and the salt locate front of a thrust forces which melt or joint lower Gypsum with chalk, as well the missing rock in the south and southern west were replaced by a dissolved breccia. See figure (3-3) (right). The figure has shown truncation surface and overlaying by upper Gypsum as well, folded of kanaite beds of unite B.

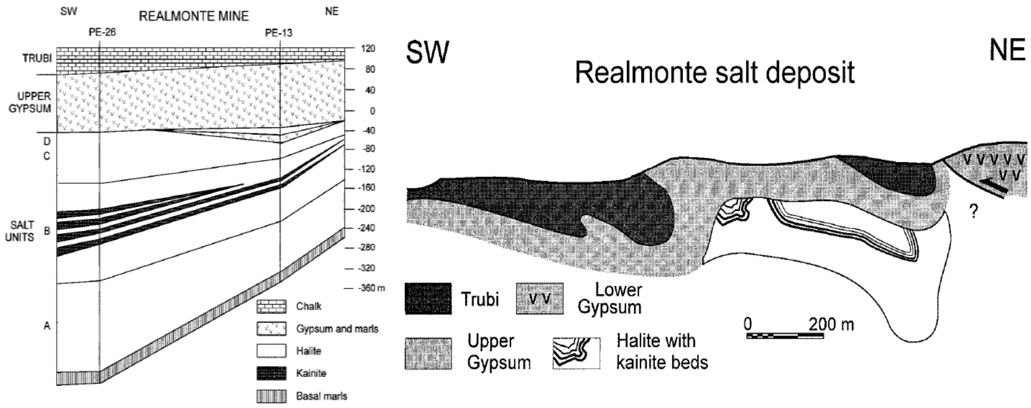


Figure 3-3 Realmonte salt deposits units (left). Cross section in Realmonte salt deposit (right) (Lugli et al ,.1999)

- **The Racalmuto mine**

The Racalmuto mine locates to the northeast of Racalmuto in the area Pantanelle-Sacchitello-Culma Prevola, the Racalmuto saliferous the name of subsurface bodies which was exploited in the central Sicily within the Caltanissetta basin. There are lot of tunnels through this mine which have been reaching hundred meters, the total maximum thickness of halite deposits reaches to 1000 meter, and was divided into two main parts, the lower part consist of halite and minor kainite and carnallite layers , while the upper part has just halite. Those two parts are separated by several inter-bedded mud /halite cycles which sometimes reached to 10 meter, and there are effecting of weathering that meaning underground water can expose the halite, dissolution pipes processing will be happened, these pipes have been shaped upturn tepee structure, and was cut by vertical fissure, this is for down part. The upper part has shown dissolution pipes and irregular truncation of the halite crystal terminations, which refer to precipitations from non-stratified, relatively shallow water body, characterizing similar to the upper part of the Realmonte mine. Furthermore, this mine salt is characterized by abundant of mono or two phase fluid inclusion. The excavation history of this mine (Contrada Pantanelle) has been recorded the best halite crystal of all Racalmuto area, it was colourless cubes (2-3) cm length of edge. See figure (3-4)

Figure 3-4 halite crystal Racalmuto

- **The Petralia mine**

The Petralia salt mine, it is an active mine which operated by Italkali company, situated between Raffo and Salinella, about 2.5 Km to the east of Petralia Sorprana, on the left the Salso river, the name of this river was derived by salt, because the erosion of salt bearing rocks in this area.

The Petralia mine has lens- shape, massive, and highly deformed salt body for this mine. It has recrystallization, and the facies is uniform as well equigranular with less impurities, farther more highly folded stratification ,with thick white halite strata alternating with thin dark clay horizons. Despite the high deformation and recrystallization, some parts of halite's still contain a small core of primary "cloudy" crystal. The salt contains micro- inclusion fluids. The modern production facilities have been installed since 1972, and more than 70 Km tunnels have been excavated, the productions cover industry and non-industrial. See figure (3-5).

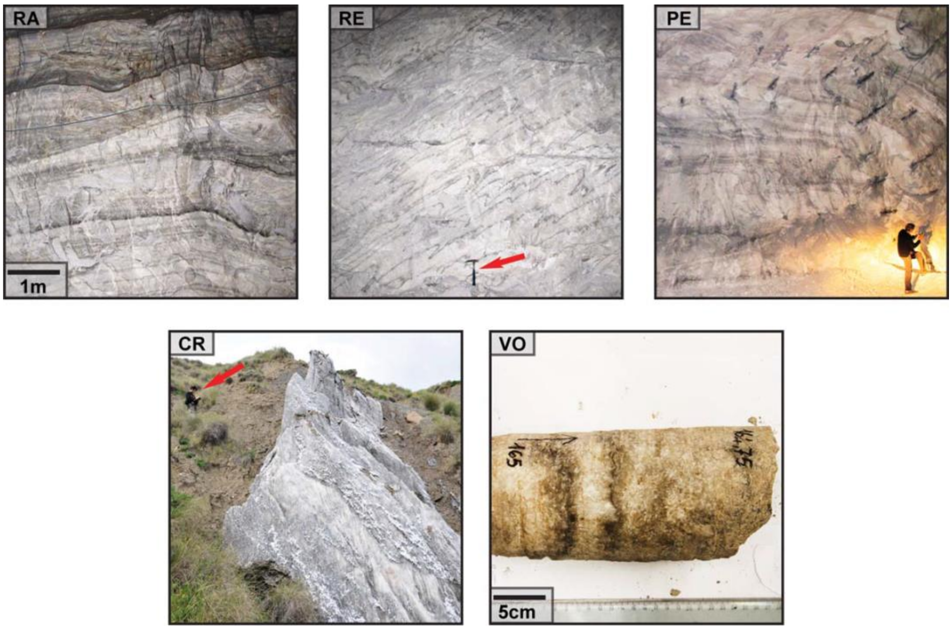


Figure 3-5 Racalmuto salt mine; RE: Realmonte salt mine; PE: Petralia salt mine; CR: Crotone Basin, Vitravo 2 diapir; VO: Volterra Basin (Speranza et al,. 2013)

3.1.2. Minerlogy of Italian rock salt

Generally the rock salt was classified depending on the source of creation crystal, primary and secondary.

- **Volterra basin**

The primary rock salt has cloudy crystals which were developed by precipitation from water or overgrowth at the bottom of water body; it was characterized with white /gray colour, also it has less amount of fluid inclusion, the most shapes which have been growth chevron, cubes, and hoppers. On the other hands, the secondary rock salt is characterized by pure crystals because it was came by dissolve and deposited or recrystallized from primary crystals.

The Italian rock salt crystals types different from mine to another, even in one mine, for instance the Volterra basin , the rock salt of this basin has been shown wide variety facies for both shape (irregularity and less than (1cm) long) that connect in deformability as well availability of clays, and primary crystals. Often the secondary crystal surrounds the primary one.it was extracted core for this basin, the bottom of this core has shown primary type salt while the top can be said completely recrystallization salt. The grain size for this basin range between (4-5) cm, also it has irregular shape. The type of rock salt is primary.

- **Caltanissetta basin (the Petralia Sottana salt mine).**

This mine as well the other two types of mines of this basin (Realmonte, Racalmuto) have been formed from secondary(partially recrystallized) type salt, variable grain size ,stratified ,and sometime are inter-bedded with K-Mg salt layers (mainly Kaninite), as well clay strata. See figure (3-6), which has shown grain size distribution size of the Petralia rock salt, (3.6 mm).

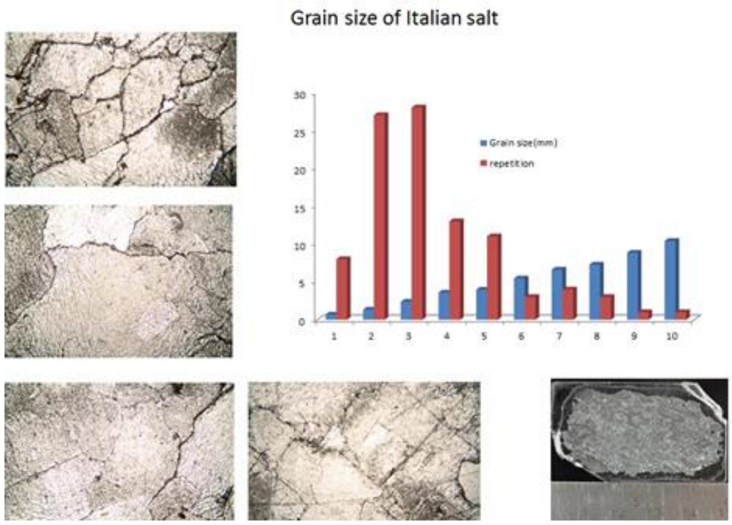


Figure 3-6 grain size distribution of Petralia rock salt.

Fluid inclusion of Messinian Halite.

Actually, the tests was published (100), fluid inclusion for different mines and basins were done, the fluid inclusion were classified into three types (A,B,C) , due to phase number, for instance , (L) was meant to one phase, which have shown cubic or rectangular shape, represent with type (A)test, while type B1, was referred to fluid with solids, while type (B2) fluid with other material, also type (C) inclusion are tubular –form mono or two phase fluid inclusion. The results have been shown that the Petralia and Realmonte salts have been characterized with type (C). See figure (3-7)

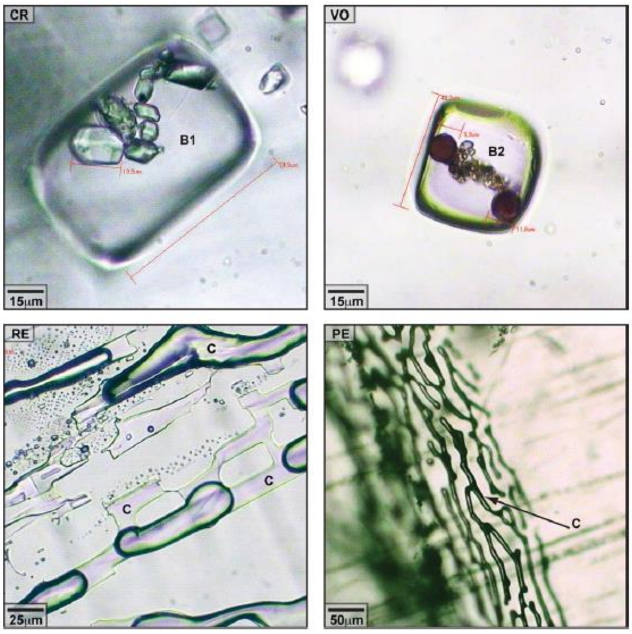


Figure 3-7 PE, Petralia , RE, Realmonte, which are characterized with type C) fluid inclusion (Speranza et al,. 2013)

3.2. Iraq rock salt

3.2.1. Lower fars formation (rock salts).

Oil and gas in general accumulate in reservoirs, which have the ability to accommodate oil and gas because availability of good porosity, permeability, and barrier beds. So, the famous types of oil and gas bearing rocks are sandstone, limestone, as well shale, while the most barrier rock, are anhydrite, compact limestone and rock salt.

Other factors can be occurred, as the sedimentary deposits basin conditions, tectonic events and depth of target which make the reaching to this target not easy but is not difficult.

Actually, as it was explained, if the rock salt will be faced through drilling plan, more attention should be done to avoid accompanied problems. The area near to the Zagros belt are characterized by tectonic events, as well inter-bedded rock salt with pressurized shale. The formation name which covers those rocks, as well anhydrite, claystone, and gypsum is "Lower fars".

The oil fields which have this formation are The Fauqe, the Abu-Girab, the Buzergan, the Halfaya, and the Noor . See figure (3-8).

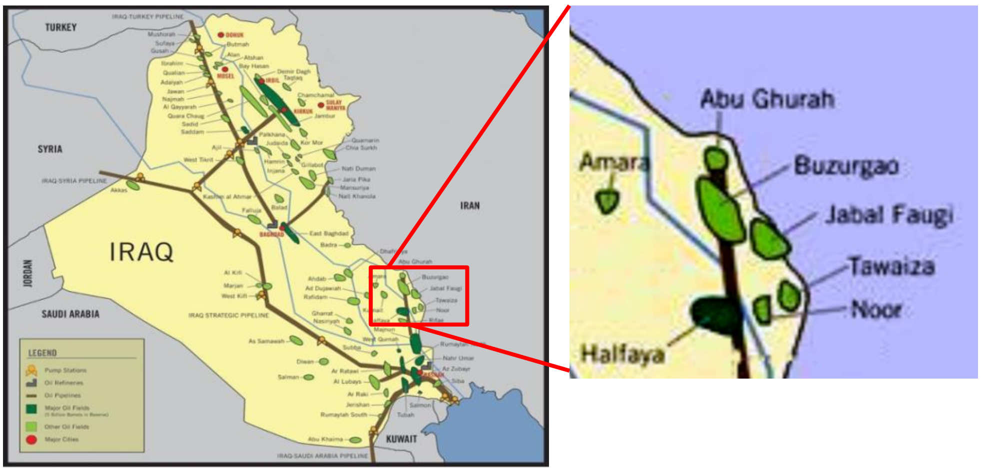


Figure 3-8 Iraqi south oil fields have lower fars formation oilfields .[http://www.bloombergview.com/articles/2006-13/u-s-and-iran-frenemies-in-iraq]

The stratigraphic section of the "Lower far" formation extends on the broader between Iraq and Iran and Iran. See figure (3-9)

“The N-trending Hercynian lineaments of the Central Arabian Arch extend far north into the Zagros fore deep. They separate on the western (Iraqi side), the massive wedge of the Lower Fars clastics and evaporites from the eastern Gachsaran salt marshes of the Khuzestan Province, (Agha Jari and Dam formations) and shallow-marine carbonates (Guri Formation) in the Fars Province. The hypersaline deposits relate to a relative fall in sea level at the end of the Oligocene. The marine connection, or ‘Tethyan Seaway’, became obstructed along the narrow foreland basin so that basinal evaporites began to precipitate in the former fore deep.”(Ziegler et al,.2001)

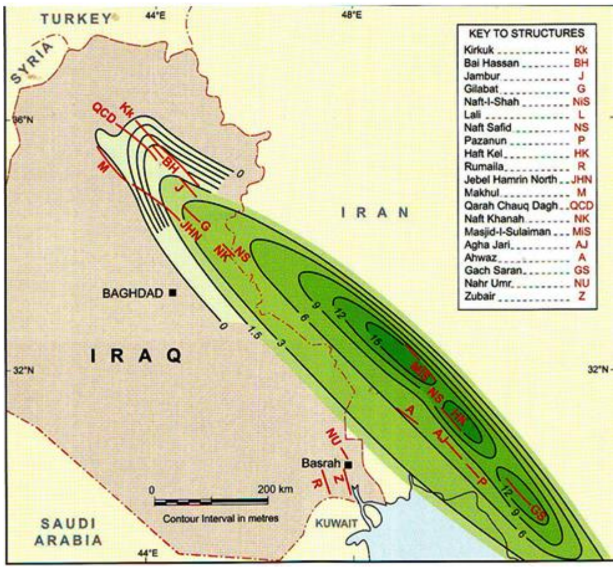


Figure 3-9 Isopach map showing the approximate original (i.e restored) thickness of the Mobile Group of the Lower fars Formation in the Mesopotamian basin and Zagros foredeep.The Mobile Group is the halite-bearing unit of the Lower fars Formation.(Aqrawi wt al,.2013).

Furthermore, Iraqi territory was divided into four tectonics zones where were characterized by type of rocks, their age, thickness and structural evolutions. The first two zones of Arabian plate, inner platform (stable shelf) and outer platform (unstable shelf) can be said on those platforms, they have not been shown any kind of metamorphism and volcanism processing. The Iraqi territory is located in the extreme north-eastern part of the Arabian plate. This plate is colliding with the Eurasian (Iranian) plate, which has been developed a foreland basin that is divided into 4^{th} zone too:

- Imbricate zone.
- High folded zone.
- Lower folded zone.
- Mesopotamia fore-deep.

Generally, the Mesopotamia fore-deep basin considers less tectonically disturbed rather than imbricate zone. See figure (3-10).

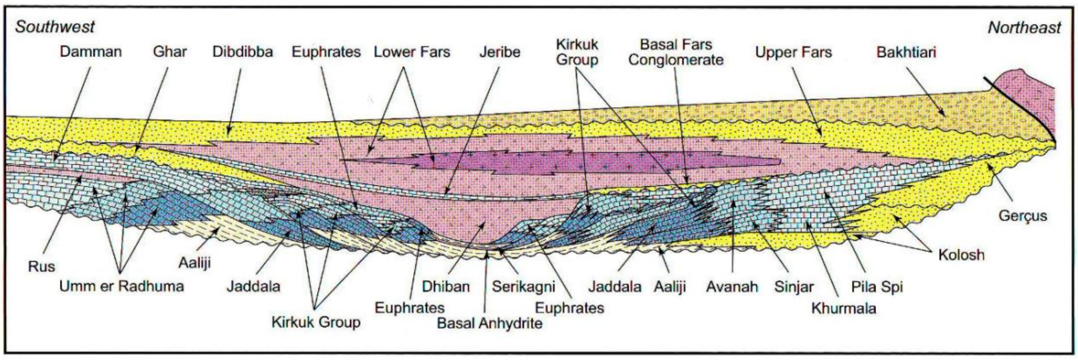


Figure 3-10 cross section in the Cenozoic Mesopotamian foreland basin in Iraq (Aqrawi. et al,.2013)

The Mesopotamia fore-deep has two plains:

- The Mesopotamia plain.
- The Jazira plain.

The Quaternary alluvial sediments of the Tigris and the Euphrates rivers was covered all central and south east of this fore-deep, which is named also the Mesopotamia flood plain, while the extension of this plain towards the northwest is called Jazira plain that covers by Miocene rocks. (Sissakian et al,.2013)(Numan et al 1997)(Homke et al,. 2004).

So, the Iraqi inner stable plain is considered part from the Arabian plate, that less effect by tectonic, which is covered the area of the south and west of the Euphrates River, however the main tectonic effect on the area of the Rutaba uplift. This Uplift is characterized that no exposure Miocene rock on it.

The Cenozoic sequences consist of Paleogene open marine carbonate, of earlier Miocene as well evaporitic rocks, and middle Miocene age. The quaternary sediments are very well developed in the Mesopotamia plain. The Iraqi inner platform is considered stable shelf which is a part of the Arabian plate, this is less affected by tectonic disturbance, the main part which is affected by tectonic, locates in area “The Rutbah Uplift” through the Jazira Plain. . See figure (3-11).

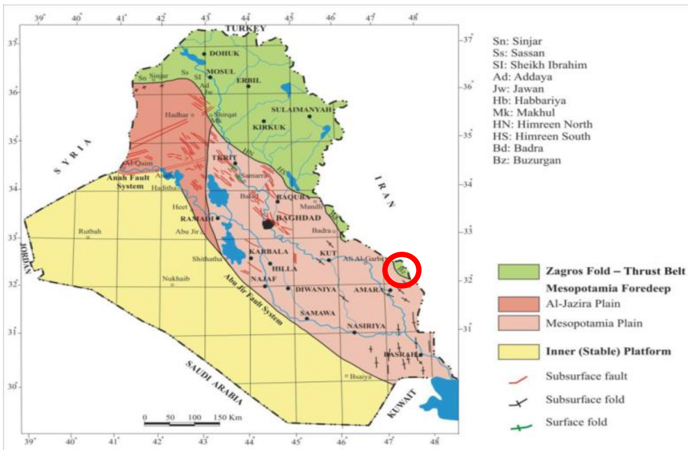


Figure 3-11 Structural map of Iraq (Mesopotamia foredeep) (Sissakian et al 2013)

However, the continental collision between Iranian plate and Arabian plate through different formations of the Zagros fold-thrust belt and associated foreland basin, activate all pre-existing faults. See figure (3-12)

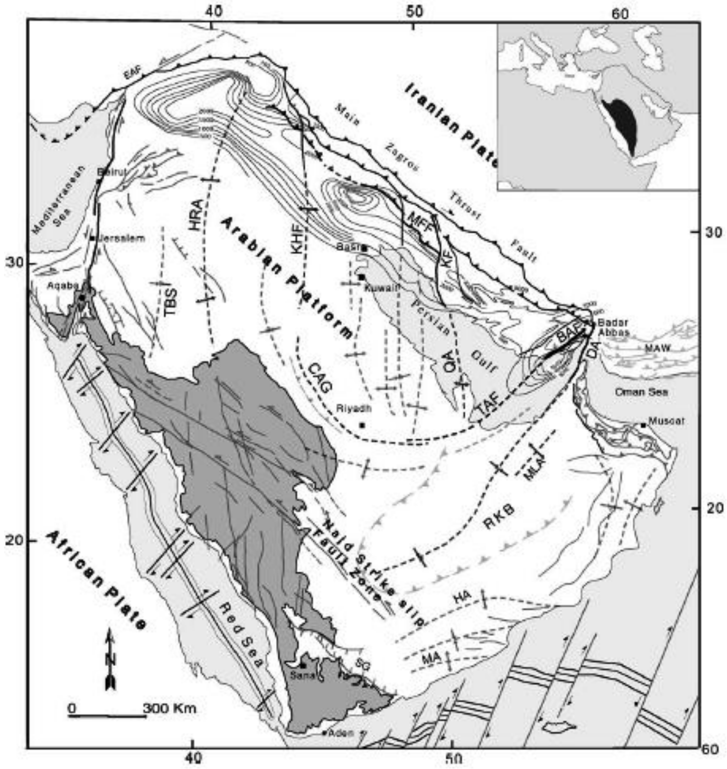


Figure 3-12 main basement faults, collision between Arabian and Iranian plates, Isopach contour of Gachsaran formation in feet. (Bahroudi et al,.2004)

The Mesopotamia plain is considered mobile tectonic zone which, contain several underground structures as folds, faults and diapiric salt. Even these tectonic events was recorded recently through their effects on the Quaternary stratigraphy and geomorphological landforms, as abandoned river channels, active and inactive alluvial fans (change in energy stream which carried sediments) and topographic expressions of some active subsurface anticline, all of these indicate for Neo-tectonic activity of this plain. See figure (3-13).

Figure 3-13 Google earth image showing a big inactive alluvial fan between Kumite and Amara, because uplifting of Buzergan (B), and Halfaya(H) substructures anticlines (Bahroudi et al ,.2004).

This formation has been put special care by petroleum sector because it has high pressure zone, which is reserved in the porous of the shale rocks, and plastic salt.

The thickness is heterogeneous, extend in range a few meters to more than 1000 meters especially in the oil field which was named Fauqi , because the regression and transgression of the sea, the depth and shape of the sedimentation base. This variation in thickness might have been controlled by basement fault movements for unstable shelf of the southern Mesopotamian plain.

This formation “lower Fars” was deposited during the Middle Miocene age.

At the same context, [most salt deposited in North of America were formed in Jurassic,Permian or Devonian period, some beds salts, have been recrystallized; and , salt from salt domes has undergone extensive recrystallization, deformation , and porosity reduction (dome salts are less porous than bedded salts, and older salts are less porous than younger salt in general), and it can expected that the Iraqi rock salt are near for these properties, (middle Miocene), as the Jiangsu china rock salt were lake deposits formed in Tertiary (Eocene) and have not undergone repeated recrystallization or large scale creep deformation associated with tectonic mobilization or diapirism .(Farmer et al,.1984)

Shale, Anhydrite, claystone and Salt as well as Limestone sometimes are the most rocks of this formation. It set unconformable on the "Jeribe formation (lower Miocene)" in area far from Basra while, set comfortable on "Ghar formation (lower Miocene)" near to Basra. Farther more, as it was mentioned, it has been taken "Gachsaran" name in Iranian part, while "Al fataha" in the northern part of Iraq.

It was divided (Aqrawi et al,.1993) into three unites:

- Unite A, siliciclastic sediments and marls.
- Unite B, (100-400) meter, 4th cycles (marl-anhydrite, marl-limestone-anhydrite, siliciclastic –anhydrite, and limestone-anhydrite).through these cycles several within variable salt thickness (1-20) meter included.
- Unite C, (100) meter limestone bed.

See figure (3-14)

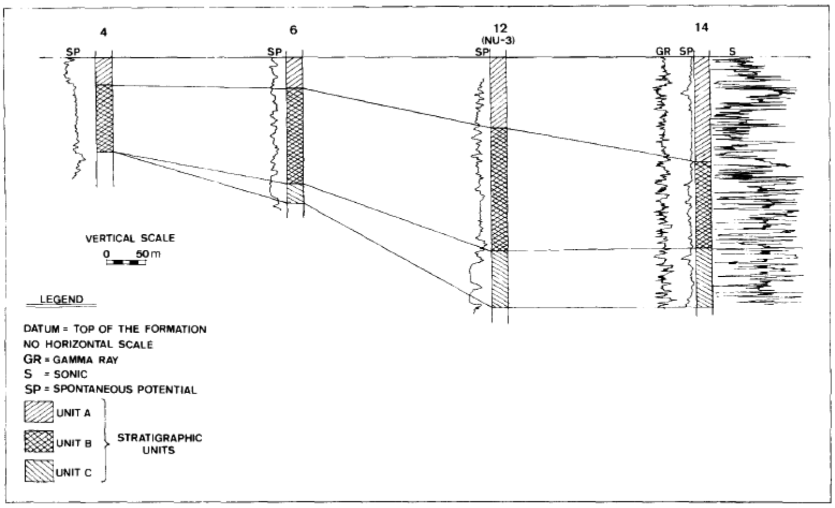


Figure 3-14 stratigraphic section (units A, B, and C) (Aqrawi et al,. 1993)

Also, It was divided for five members, and the thickness are variable from field to other, but was increased in ward east and north east till reach approximately (1050) MT in some field. The “Lower Fars” formation is characterized by abnormal pressure rocks (member 3). Due to abundant of the shale, this rock retained water under high pressure in impermeable materials. The Shale was restricted by hard impermeable anhydrite that will not permit for any fluids to escape.

There are different reasons which consider the Lower Fars is important formation:

- First: this formation has abnormal pressure and changeable through itself to become normal in front of member no.2.
- Second: The member 1 of the lower fars (Anhydrite and dolomite inter-bedded with rock salt) is considered a weak zone, comparison with high mud weight used for drilling borehole. The most important bed of the bottom part for Lower Fars (member 1), that make the cap rock for the production zone (Asmari), which consists of oil bearing sandstone with normal pressure. So, two different beds with two pressure gradients (the difference in gradient approximately 1 gm/cc), if it do not recognized well, it will be serious lost circulation mud through thin permeable beds which was deposited between Anhydrite rocks, that lead for many risk problems, and may be will lose the well.
- Third: this formation has lot of salt beds with different thickness The lower Fars formation represent full sedimentation cycle begun with transgression of the sea then regression through middle Miocene age, this formation in the south of Iraq had been set above formation from lower Miocene and this formation also has other name in Iran.it was called there Mieshan/jarran) the same in Saudi Arabia ,was named Al- Dam(parous 1966) and the same name in Kuwait ,the thickness of this formation has increased towards Iran.

The north part of Iraq this formation was divided for fourth members depending on the repeating of Limestone, Anhydrite, salt and clay, the sequence of these members from top to bottom:

- The red bed.
- The seepage bed.

- The beds which have salt
- The transition bed.

The south part of Iraq, this formation was divided for 5th members as follow from top to bottom:

- Mb5 Anhydrite, Shale.
- Mb4 Salt, Anhydrite, Shale.
- Mb3 Anhydrite, Shale, Salt.
- Mb2 Salt.
- Mb1 Thick Anhydrite.

And in the south part too close to Kuwait this formation was contracted to three members from to bottom:

- Unite A most of it unconsolidated rocks.
- Unite B different cycle of sedimentation of carbonate rocks, unconsolidated and evaporated rocks.
- Unite C Lagoon Limestone.

Despite the Lower fars formation, has been covered by different studies but these studies have been focused on the northern part, while the southern part has been still do not cover well, may be the reason that connect by outcrop of this formation in the north of Iraq . This outcrop assists researchers with raw material. The lower fars has big and thick evaporated sequences in the geological column of the middle east.

Furthermore, the Lower Fars in generally is considered as a good cap rock for a good oil accumulation" The Early Miocene hydrocarbon development along the northern Zagros foredeep is to a large extent controlled by the distribution of evaporate cap rocks of the Lower Fars and Gachsaran formations . The extensive Gachsaran salt and evaporate deposits are the seal to the Asmari oil accumulations in the Khuzestan-western Fars region of south western Iran. ".because the salt beds in general have very small porosity and can say impermeable that represent a good seal for these accumulation.

3.2.2. Minerlogy of Iraqi rock salt

Unfortunately, the mineralogy and morphology tests were not done for this rock salt even there are not studies which can cover this type of rocks from both sides Iranian and Iraqi sides, might be the reason behind that connecting with the privacy of working oil companies.

General information’s available, for secondary type of the rock salt, can give us a good view for this rock , in the area of the interest in both sides (Iranian , Iraqi) ,its secondary rock salt because the location near to active tectonic zone. It has big grain size extending between (50-80) mm. The XRD test has shown, small amount of Anhydrite and Ankerite with rock salt. See figure (3-15). (3-16).

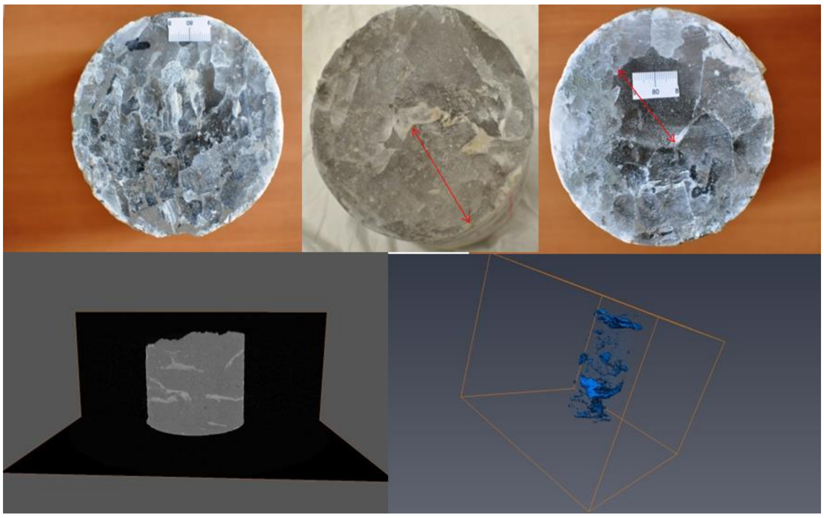


Figure 3-15 upper different slides for grain sizes, lower X-ray for the same piece of Iraqi salt shows the anhydrite through rock salt.

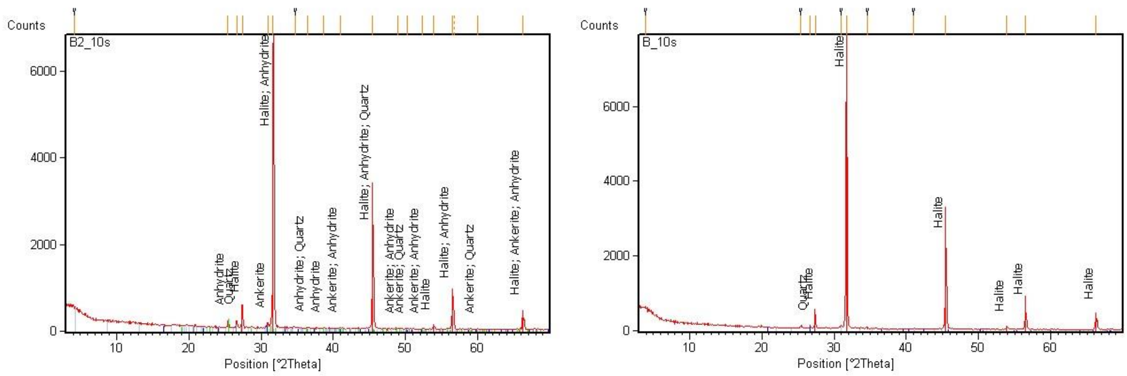


Figure 3-16 XRD-test for samples of Iraq rock salt

Chapter 4: Geomechanical testing for selected rock salt

4.1. Testing Program

The target of this chapter is to characterize the Italian rock salt by applying the standard experimental test. The most important mechanical properties are needed in the most constitutive model. Those properties have been included static Young modulus, Poisson ratio, yielding, hardening, creeping, failure, and residual strength. Generally the experiment is very important for any research because through it can study the effect of a variables effecting on the problems. So, the standard tests which are included:

- Brazilian test (tensile strength).
- Uniaxial compressive test
- Multistage tri-axial test
- Creep test
- Constant mean stress test.

To get good results from any standard tests, the care should be taken for preparing rock salt specimen because the mechanical properties are so affected.

There are different reasons to evaluate the Italian rock salt as well the Iraqi rock salt:

- It was chosen the Italian rock salt to support the thesis.
- Both of them are primary rock salt.
- Both of them from the same geological age (middle Miocene).
- Shorting in raw material of the Iraqi rock salt.
- It can be evaluated the Iraqi case study by using the Italian rock salt.

4.2. Core storage and specimen preparation

It’s worthwhile that this thesis was supported by rock salt which was extracted from depth reach (2584) meter, and because the cost which connecting with extraction, the amount of this raw material was restricted. It has just (100 mm x 600 mm), distributed to 5th irregular ended pieces, because the transportation from Iraqi to Italy. See figure (4-1).

Figure 4-1 Iraqi rock salt in oil well site, and block of Italian rock salt (laboratory).

It has planned to use Iraqi rock salt under boundary value problem test (hollow cylinder), and it was extracted other specimens to evaluate it under standard tests as the Italian rock salt.

Many thanks to Italiak company which responsible for production line of Realmonte, and Petralia mines, which has supported the thesis by abundant amount of rock salt. It was stored in dried condition; the same was done with Iraqi salt.

Samples for geo-mechanical testing generally require specific dimensions related to available testing equipment’s (constraints on diameter), length to diameter ratio. The right cylindrical samples were prepared according to ASTM standard D 4353-08- Specimen Preparation. This standard specifies that the diameter of specimens for strength testing should be a minimum of ten times greatest than the largest crystal size within the sample.However, these requirements could not be met for the majority of salt core, as the crystals ranged from 10mm to 70 mm, as it’s in the Iraqi rock salt but it’s compatible with Italian rock salt.Most published articles which have been working on rock salt, are being suffering from cutting the specimen of rock salt. Different methods was mentioned, one of them(Fuenkajorn et al 1988) was used air for cooling and clean the cutting head which should be rotated slowly (120-150) rpm, other method, which used salt saturated brine for cooling , and clean the cutting head, with speed(600-750) rpm, but generally, if it can use big diameter (more than 54 mm), the coring will be success.

It has used in this thesis, new method to extract the core specimens by using simple system, that has used aerated brine and cutting with speed reach 600 rpm, after the coring, the specimen was dried by using temperature 100C.

The rock salt specimen should be covered by plastic sheet, and then using diamond cutting disk to get the required length, while the brine has used to cool the cutting tool, finally, grinding machine has used with small amount of brine between the grinding block and face of specimen to get parallel ends (trying to meet the tolerance as prescribed by ASTM standard D5443), then the specimen would be put in an oven to dry it. See figure (4-2)

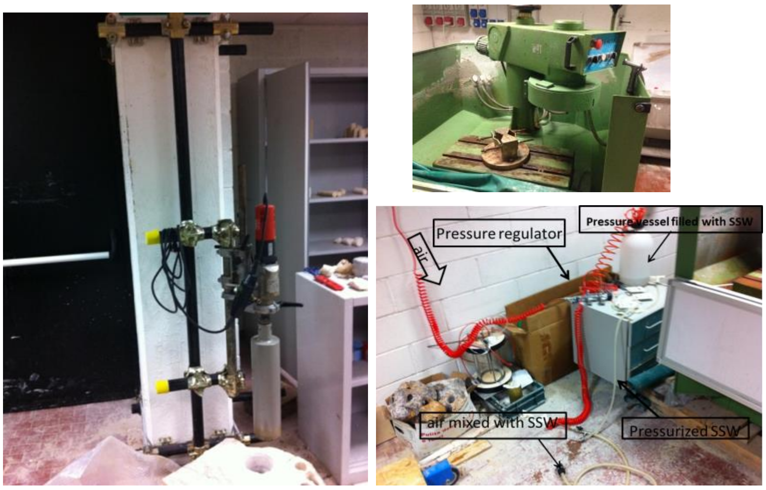


Figure 4-2 left), frame for coring. upper right), grinding machine, lower right) parts of aerated SSW for cool and circulating coring system.

4.3. Ultrasonic wave velocity

This is indirect means to evaluate geo-mechanical behaviour of the samples which belongs to the same formation because the measurement of the velocities (shear wave, and compressibility wave) can help to assess homogeneity of rock. Also, it can extract the dynamic elastic properties. It's possible to use these techniques when perform BTC, UCS, CMC, CME, STC and creep test.

The apparatus consisted of two transducers; one will be the source pulses, which works as transmitter to convert electrical pulses to mechanical pulses, while the other one work as a receiver that convert mechanical pulse to electrical pulses. These sensors should be connected to a sonic pulse generator "Philips Oscilloscope" on which the signal could be read.

A calibration should be done by using standard specimen as a stainless steel or aluminum specimens that have the compressive velocity and shear wave velocity known. It has used compressive velocity with uniaxial compressive test, in order to measure the deformation factor which can be measured by using compressive sonic velocity.

The standard test method in laboratory has been followed (ASTM D245-08), to determine the dynamic elastic constants of the rock salt from velocities and ultrasonic. The vacuum grease has been used at the ends of samples to facilitate the transmission of the signal. UCS uniaxial compressive test accompanied with compressive wave velocity measurements has achieved, but unfortunately, without using shear wave velocity. However, the extracted data by ultrasonic apparatus has used to calculate the damage factor. See figure (4.3).

The micro-fracture during uniaxial test, can be followed by using acoustic tool, because the permeability increase, if a specimen do not be confined and was under high stresses. The damage factor (D), can be calculated by using compressive longitude velocity before test and during the stages of test:

$$D=1-(V_{pd} / V_p)^2 \quad \text{…………………………(4-1)}$$

V_{pd} longitudinal wave velocity under loading.

V_p longitudinal wave velocity before the test.

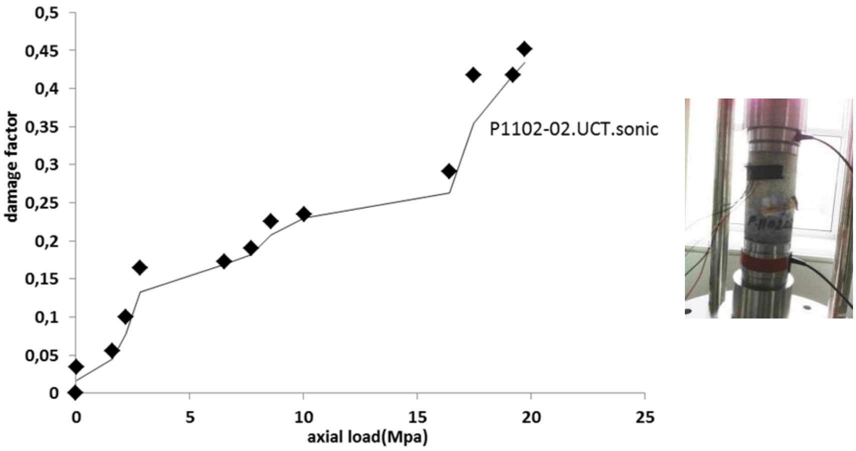


Figure 4-3 damage factor vs axial load for uniaxial test (P1102-02)

The figure has shown different trends, the first trend has shown closing a natural micro-fracture that reflect low damage factor. In the elastic region the damage factor trend has changed from steeply to gradually, while the last trend, the damage factor has changed steeply because the specimen has entered in yield, failure state.

It's clearly, when the loading increase, the micro-cracking damage will increase, so the longitudinal wave velocity has been shown decreasing too. Despite of the acoustic tool should be used with a cubic specimen, rather than cylindrical specimen, because measurement will be good, as result wave velocities perpendicular to the direction of loading on the specimen.

The cubical specimen can give us the ability rather than cylindrical specimen (Chen et al, 2013). However the figure give us clear view for the micro-cracking development, but for the best result, should study effect of temperature during triaxial test to discover salt healing in hydrostatic part for instance.

4.4. PIV technique

Many sectors of the life use PIV. It has applied for different materials as biological materials, metal, polymers and geo-materials. Due to the attempted to create apparatus that can use to apply hollow cylinder test, here it has introduced PIV technique to overcome measuring problems inside a borehole of the Hollow cylinder rock salt test, and the long time for creep test.

The PIV techniques, has tested to know the ability to measure the strain of the rock salt under Brazilian (BTS) and uniaxial compressive (UCS) tests. A few experiments was done to test this method for rock salt, PIV was used for different rocks, but the majority of using PIV in soil mechanics. It has been using for measurement of soil deformations in geotechnical models .Particle image velocity (PIV) techniques — also known as digital image correlation (DIC) and it has been became routine experimental practice in many geotechnical research laboratories over the past 15 years.

The capabilities of the algorithms and analysis techniques that underpin PIV–DIC have also improved significantly over the same timeframe. PIV is able to extract wide range of deformation which is usually taken different pattern displacement or rotation under loading, all techniques are used in PIV, starting from region of interest area (RoI), based on the first photo which is called (reference), when the specimen is not experienced.

Every PIV models are populated by subset meshing, which considered important step because; the model will build all processing on this meshing, which is called "Patch" too. So, the displacement of this subset in subsequent images (targets) is followed by using different types of approaches. See figure (4-4).

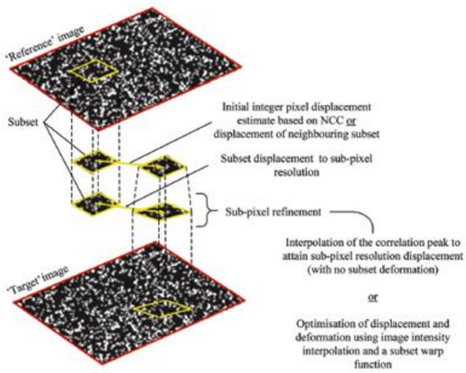


Figure 4-4 PIV-DIC analysis overview general overview of PIV-DIC method (Stanier et al ,.2015)

Most PIV-DIC software that is used for geotechnical analysis is free, it was based on form of cross correlation to obtain integer pixel displacement followed by, subpixel interpolation of correlation peak (Stanier et al ,.2015)

through all of these algorithms, the subsets (Patches) are generally not allowed to deform (zero order deformation), meaning the computational methods restricted in the reference image, which is called "leapfrog", and here the calculation will be suffered to lose the correlation when the area of interest will be experiencing large deformation. See figure (4-5.a).

On the other hand, the second improvement method, which was updated the reference image during every stage of computation, which is called “sequential”. However the mismatch is still in shape function. See figure (4-5.b). The other improvement that was developed," preconditioned optimisation", scheme with first order subset shape function. Figure (4-5 .c)

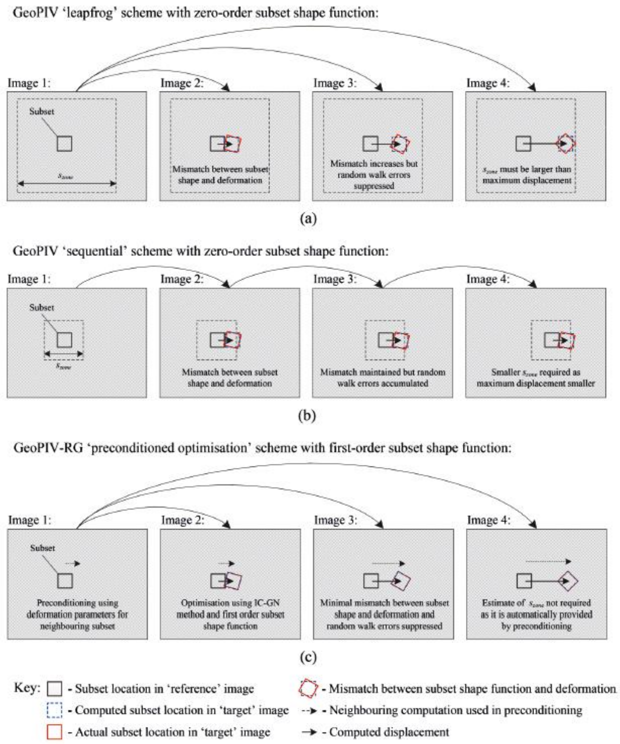


Figure 4-5 overview of the expected evolution of correlation coefficient (Stanier et al ,.2015).

4.4.1. Selected method for PIV analyses

The method is used here, Ncorr. This method has flexible codes, which can users freely adapt to suit their needs, the package is implemented in MTLAB (http://www.mathworks.com/products/matlab/), and it was written in C++ and incorporated into MTLAB through MEX interface which is given greater efficiency for computing. A Graphical Use Interface (GUI) can help and assist in analysis

For more details to the Ncorr algorithm (Balber et al ,. 2015),. The reference image in Ncorr is divided into smaller regions referred to as subsets or sub windows, and it was assumed the deformation inside each subset homogenous, and it is followed, a track for next sequent image.

The subset is not a shape and tracked this shape, as the most PIV, but it’s a closest group of points that are on integer pixel location in reference image and will tracked the coordinates of these points into sequences of images. , the relation that connect and constrained these point for transportation from reference to current image, are linear. (First order transformation), any changed in horizontal and vertical direction, which meant deformation in (u), and (v).See figure (4-6).

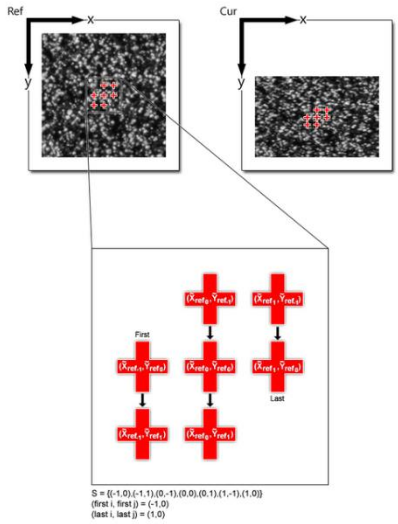


Figure 4-6 The subset’s coordinates are shown as red crosses .the subset do not need to be square ,as shown above; the shape can be arbitrary as long as it contains a center point.

The changing in coordinate due to displacement will be taken relative to the center of these points, as well the difference between current and reference images .The configuration, of group points can be taken the general form of the deformation vector.as it has shown in figure (4-7).

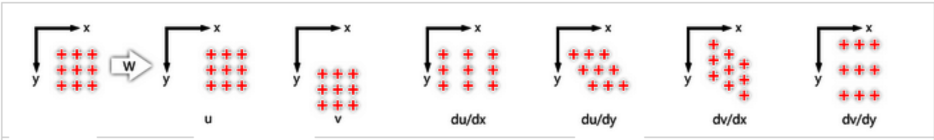


Figure 4-7 linear transformation for subset coordinates, any linear combination of 6 parameters shown above can be used to deform subset coordinates through warp function.

In order to find deformation in subset, two correlations was used in Ncorr, one is called initial guess correlation which is normalized on computed integer location (NCC) and the other is called iteration , which will refined till the exact solution.

The next step that is used is to establish a metric for similarity between the final reference subset and final current subset. This is carried out by comparing grayscale values at the final reference subset points with gray scale values at the final current subset points. The following two metrics are the most commonly used in (DIC).

4.4.2. Application PIV in BTS

The PIV has used through different experiments; BTS and USC. It has applied two PIV programs (PIV lab, DIC) as well as (Ncorr), in order to make comparison and to know which the best method. The calibration for those methods has done by compare experimental data for two points (fixed and moved) of the loading frame, for the fixed point. See figure (4-8). The figure has shown the best agreement between experimental points and those measured by Ncorr method, compare with the other two methods.

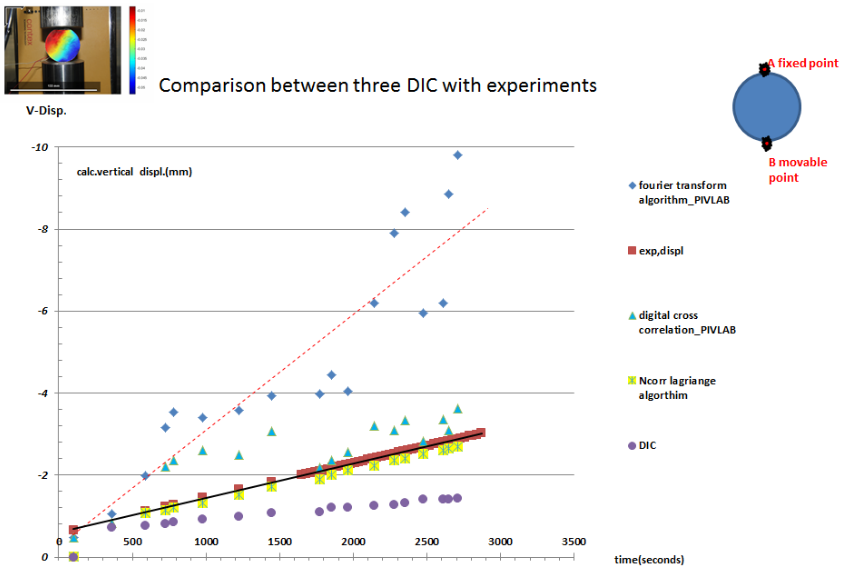


Figure 4-8 compare the displacement vs time with three methods for in Brazilian test.

Furthermore, the figure (4-9) has shown comparison the results for the moved point into the loading frame, also the method Ncorr have been shown more agreement than the others. The percentage error to use this method compare with experimental part, is (0.08346%).See figure (4-10).

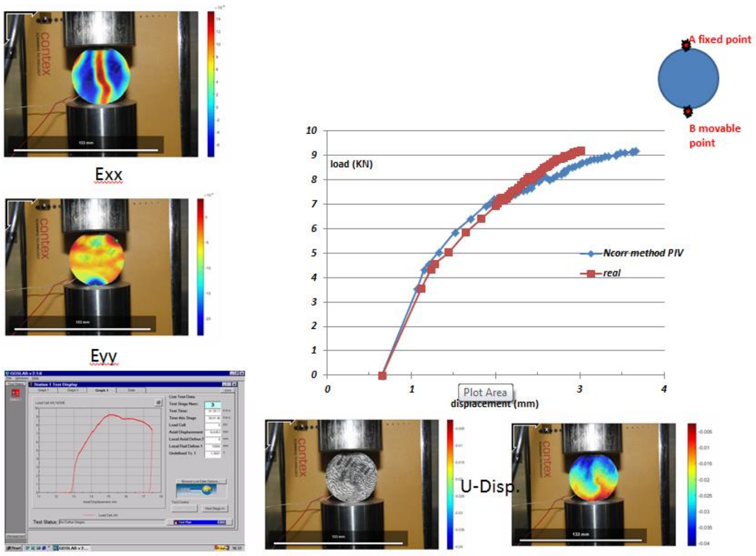


Figure 4-9 load vs displacement values for experimental and Ncorr results to the Brazilian test.

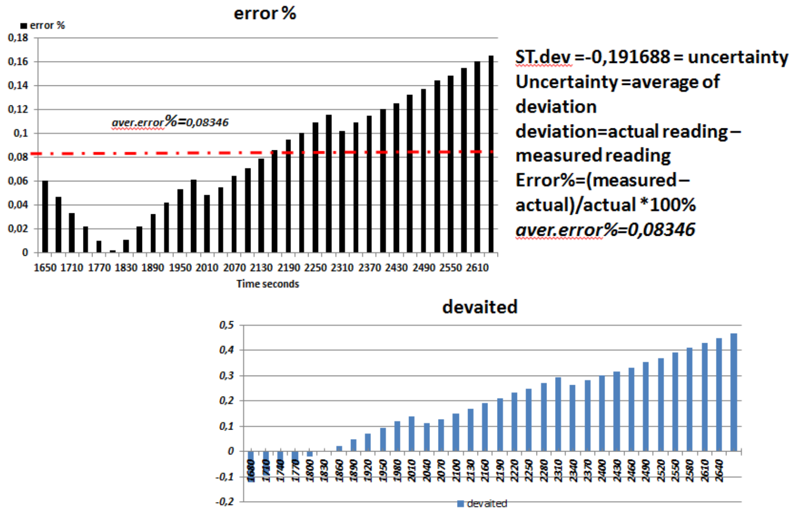


Figure 4-10 the percentage error of Ncorr. Method

Tensile strength test has done for Iraqi rock salt which is characterized by large grain size compare with Italian rock salt, and PIV has used also with it. See figure (4-11).

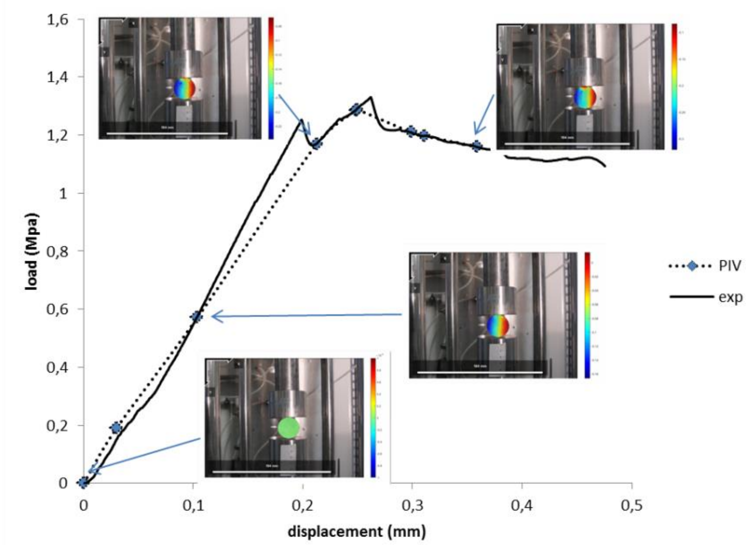


Figure 4-11 PIV technique with tensile test of Iraq rock salt.

Also, This method has used for uniaxial compressive test, and the results are good because the rock salt generally shows large deformation, and the measurement of this deformation most of time has been considered as challenge from experimental point of view. See figure (4-12).

It is clear the accuracy of this method; therefore it has given the motivation to develop apparatus which help to simulate the Iraqi case study.

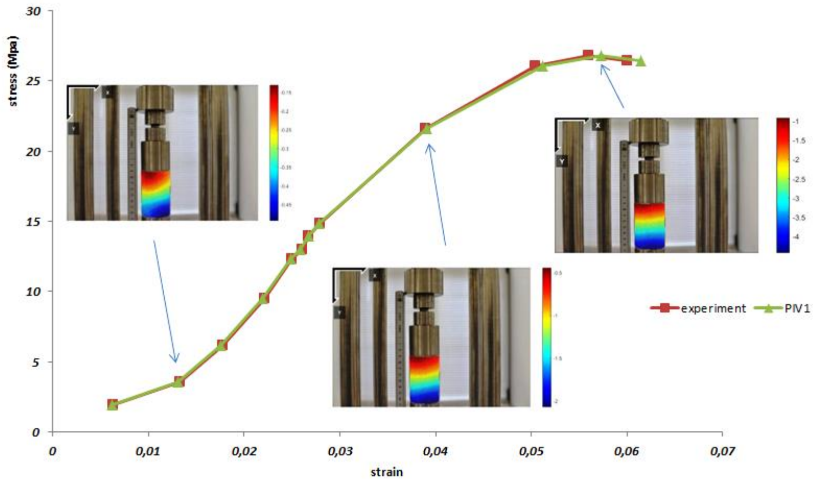


Figure 4-12 UCT test was measured by Ncorr method.

Summarized results from experiments

The deformation of rock salt shows different ways, creep is the main pattern , which depending in some part, on lattice deformation, while the other part overcome the lattice to a grain boundaries, and then will develop to initiate micro-cracks, finally it will develop from damage case to failure one. All of these stages can be investigated by following different experiments, and then can extract the data that will cover many regions for rock salt behaviour as follow:

- Failure criterion that can be detected by using uniaxial and tri-axial test to get strength of material which is depended on strain rate, confining pressure, temperature, humidity, grain size…etc.

- Damage criterion which is characterized by increasing volume after exceeds the (compressibility /dilatancy) boundary, (no volume changing), it can be investigated by using different methods (acoustic emission, acoustic velocities, volume changing); here it has investigated by using fluid volume changing.

- The transition between compressibility to dilatancy is strongly depending on confining pressure, because the dilatancy is significant under low confining pressure, while at high confining pressure the rock salt will be under ductile behavior without failure while the failure after damage will be very clear in brittle behaviour; it can be discovered by using CMT.
- Plastic deformation point, or the damage threshold which is correlated by using uniaxial compressive strength , the ratio between damage threshold to peak strength for all uniaxial test extend between (0.4-0.5), and of course these ratio will increase when apply confining pressure.
- Effect of strain rate on the failure of rock salt has been studied, usually the range of strain rate extended between (10^{-8} -10^{-4})1/s , some literatures have been shown the failure occurred under steady state creep with strain rate 10^{-10} 1/s ,however in our case the strain rate at failure has occurred at 10^{-7} , and the damage has happened not during load but before .
- Study the effect of temperature, which play big role by increasing the chance for balancing between strain hardening and recovery processing, which means steady state creep, however, low temperature has been effected significantly on transient deformation, farther more, the peak strength of the rock salt has decreased clearly even the temperature did not increase too much compare with other experiments in other literatures.
- Improve the solutions for measuring devices under high pressure, and overcome strain gauges issue by using PIV technic ,

4.5. BTS (brazilien indirect tensile test).

Generally, the tensile strength of a material is a measure the ability to resist uniaxial tensile loads without yielding or fracturing. A direct pull uniaxial test is not easy to apply to rock, so it is used indirect test to get a tensile strength. The Brazilian test one of indirect method to get tensile strength. The apparatus which has used to do this test consist of a GDS VIS (450Nm-750Nm) loading frame, the data logger 8th channels pad (Parallel/ Serial data acquisition GDS) which has used with loading system, and GDS software has used for recording the data.

Two methods have used for measurements of tensile strength, the first that use curved platens, which resulted in the salt samples conforming to the curved shape of platens before failure occurred, thereby distributing the load over a larger area which resulted in misrepresentative tensile strength values. The second one that use direct pedestal loading to the rock salt specimen without curved platens, the results are good.

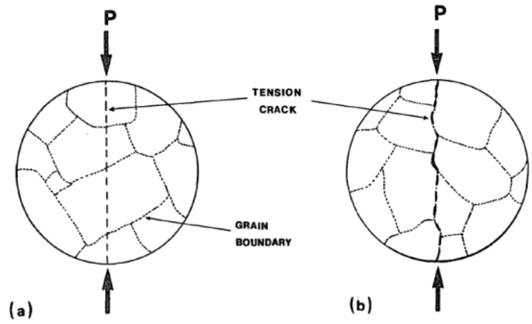
Brazilian test is one of the oldest techniques to measure the indirect tensile strength of rock, which is considered strongly control the deformation characteristics, load bearing capacity, and damage of any kind of geomaterials.

In addition, it is one of the important parameter for design and stability of underground caverns, geothermal energy system, radioactive and toxic material storage sites, hydraulics fracturing operation in oil wells.

The rocks generally are very weak under tension rather than any other kind of stress, that give the tensile properties lot of interesting to study, farther more most of these geo-technical structural operate under different ranges of temperature. So it will be very interesting to study this behaviour with temperature effects.

The temperature decrease the strength of rocks in general, some studies had been done for a range of temperature reach to 300C for enhanced geothermal systems, and the range of temperature that has used in this thesis about (26-86)C.

Many factors effect on this test, but the grains size, and their distribution has been directly drawn the way for main crack which initiated. The crystal of rock salt bears more tensile strength rather than boundary, so the fracture the through the grain will need high load, while less along the boundary of grain. So, a ratio of the grain size to the size of specimen affect directly, if the grain size will be relatively large, which enhance the boundary grain cracks, especially when weakness bonding between grains. (Larger specimen will decrease the effect of grain size). This effect has been seen in Iraqi rock salt. See figure (4-13)



Failure of Brazilian disc specimen. (a) Tension crack cuts through salt crystals resulting in higher tensile strength. (b) Tension crack induced along the crystal boundaries results in lower tensile strength.

Figure 4-13 grain size and distribution effect on the failure mode in Brazilian test for rock salt (Fuenkajorn et al,.1988)

Then, it is easy to fail under tensile strength in boundary of grains rather than grain itself. See figure (4-14).

Figure 4-14) tensile crack easy along grain boundary rather than through grain (Italian salt photo before and after Brazilian test)

The effect of grain size can be recognised generally, when it look the same test on Iraqi salt, which has (50mm) grain size compare with Italian salt (3 mm). See figure (4-15).

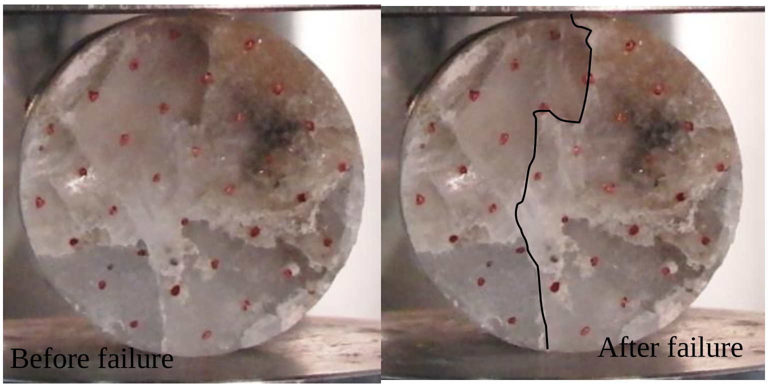


Figure 4-15 failure around larger grain for Iraqi salt A.5.1.1

Effecting of bedding plane, even the Italian rock salt do not have clear bedding plane, but some specimen has shown some impurities which deposited through rock salt, which is settled down as bedding plane. See figure (4-16), and if it considered as bedding plane, of course will effect on tensile behaviour.

Figure 4-16 Italian rock salt specimens with bedding orientation

Parts of published articles have been taken the effect of bedding orientation. On the other hands, other parts they have been taken effect of temperature and bedding orientation (Roy et al,. 2016). A lot of experiments were done for different orientation specimen (0, 30, 60, and 90), which was called inclination from vertical. See figure (4-17).

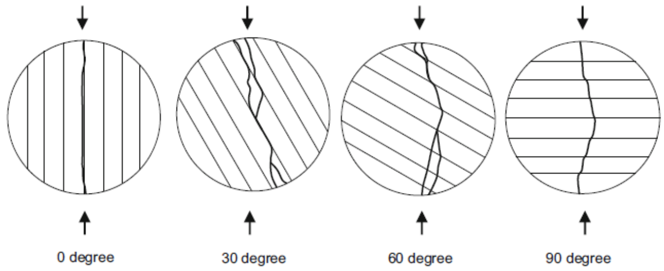


Figure 4-17 crack geometries for granitic gneiss at different “inclination angles (Roy et al,. 2016)

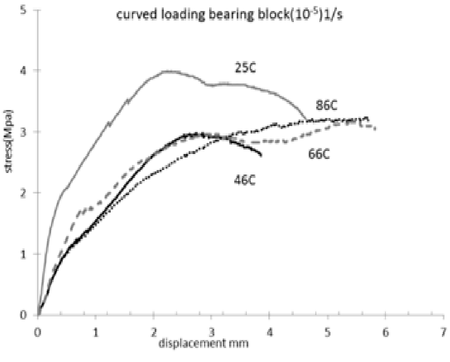
4.5.1. Temperature effect on strength tensile test

The tensile strength tests of Italian rock salt have done by using two methods,

It has used two methods:

- Curved block platens.
- Point load method without curved block platens.

As it was mention, there are two methods for tensile strength measurement, have used, because the first method has been given high tensile strength value compare with the second, the Italian rock salt responded for the curved shape of the platens directly before the failure occurred, thereby distributing the load over a larger area which resulted in misrepresentative tensile strength value, or can be said the salt samples conforming to the curved shape of platens before failure occurred. However both of them have shown the same behaviour that the tensile strength decreases when temperature increased. See figure (4-18), (3-19), (4-20).



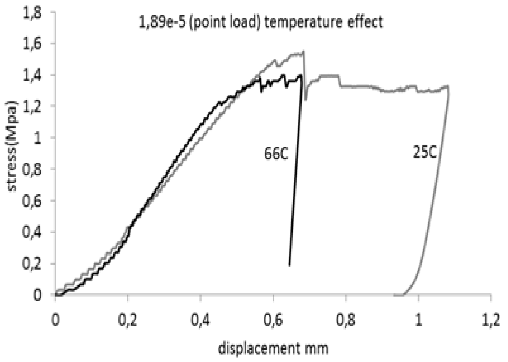
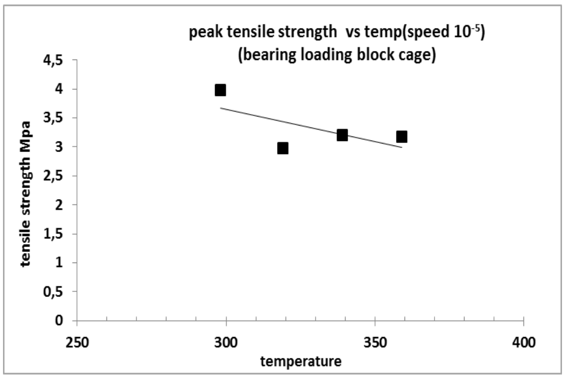


Figure 4-18 Effect temperature on tensile strength, Left) curved shape platen. Right) point load method. (Both of them was done strain rate10-5).



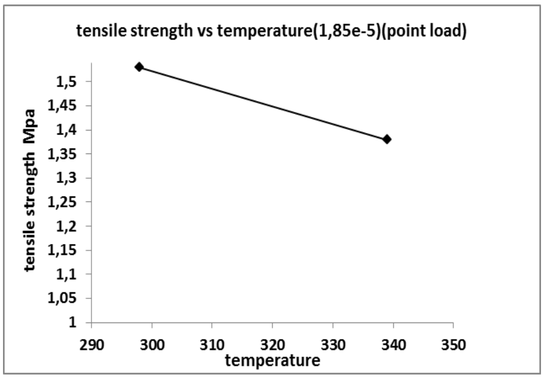


Figure 4-19 comparison between two methods for tensile strength as function of temperature.

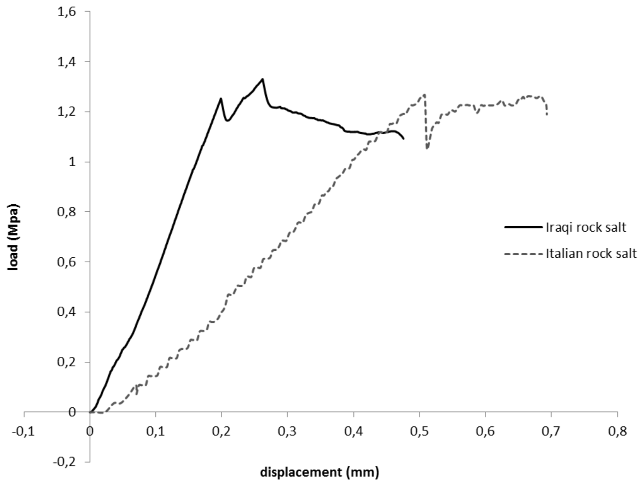


Figure 4-20 Comparison between Tensile strength test of Iraq rock salt, and Italian rock salt at room temperature

4.6. The unconfined compression test UCT

The unconfined strength stress when the lateral stresses will be zero, its simply tri-axial test when confining pressure will be zero. It will get the lowest estimated of material strength, for instance from this value which can apply some constitutive model, which is needed this value.

In order to get elastic, shear strength, compaction and failure response, all of these values based on solely unconfined compressive strength.

So, it can be seen form initial elastic stress-strain response of unconfined compressive test to calibrate Young's' modulus and Poisson's' ratio by applying Hook s' Law for uniaxial stress.

$$\varepsilon_{axial} = \sigma_{axial} / E \qquad \text{……………. .(4-2)}$$

$$\varepsilon_{lateral} = -(v/E)\sigma_{axial} \qquad \text{……… ………(4-3)}$$

So, from this test, it can obtained the deformation modulus, the peak compressive strength, and post peak behaviour (brittle or ductile) which can show to use the influence of geological factors effects on intact rock (high stiffness companion with very brittle behaviour to low stiffness with ductile), the most important factors that effect, it's the discontinuities and rock structures, which has represented by an in situ pre-existing state of stress and fractures.

The same frame and data logger in the Brazilin test; it has used with UCT and all the tests have done in accordance with ASTM standard test method of compressive strength and elastic moduli of intact rock core specimens (D7012-10), the test is under displacement control mode. The typical deformation rate is in the range of (0.15-0.3) mm/minute, while some tests have done with the same rate that has done in multistage tri-axial test, (0.12 mm/minute). However, different tests have done under different strain rate in order to see the effect of strain rate (10^{-4}, 10^{-5}, 10^{-6}) (1/s) on the Italian rock salt, as well temperature effect.

4.6.1. Mechanical properties by UCS.

Most models calculations need to have good knowledge of elastic modulus because it is used to determine the stiffness of the system or part of it, which lead to predicate the distribution of stress and strain in space and time.

However the measurement of this modulus is not easy for rock salt because the effect of ductile behaviour of rock salt, on the other hand, this effect will not be in hard rock when this rock do not have joints.

This problem can be overcome by performing fast experiments, were creep has not chance to come into effect (Cristescu. et al,.1994), so as it has pointed, that the dynamic elastic modulus is very logic result from physical point of view by using ultrasonic waves, as well it is temperature dependent, farther more depend on also on damage (micro-cracks)in the rock (Cristescu. et al,.1994)

It has followed the same method which explained (Cristescu. et al,.1994). See figure (4-21).

The good estimation, has detected at the middle third of unloading , because at the first third ,there is some forward creep ,as well the last third shows backward creep, which is cause by long range back stress. Furthermore, the virgin sample has shown smaller Young modulus because the effects of transient creep strongly, and the author has recommended naming it as, “loading modulus” which will be less than dynamic value about 20% to 50%.

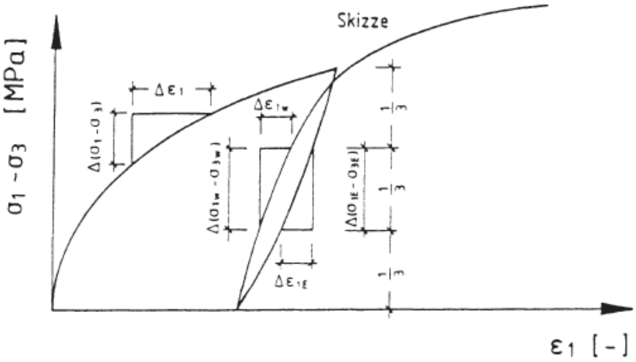


Figure 4-21 Schematic diagram showing the determination of elastic modulus E from initial loading, unloading and reloading (Cristescu. et al,.1994).

In the same context, USC test has done, and determined Young modulus by cycles loading unloading during development of strain deformation, it can be seen in the figure (4-22), and the gradually increasing in the Young modulus, till reaching the fail, the behaviour was being changed.

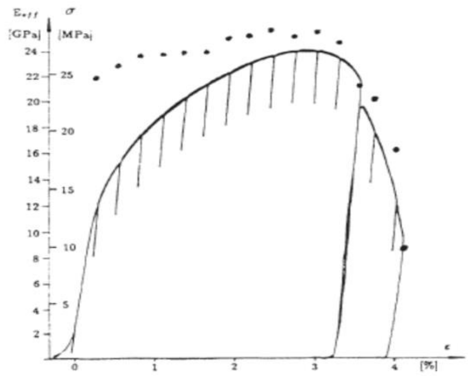


Figure 4-22 Evolution of the elastic modulus E [•] for a rock salt specimen with increasing strain determined from unloading cycles; strain rate =l0^{-4} s^{-1}(Cristescu. et al,.1994)

Generally, there are different ways to do most of experiments; under load control and strain control, for linear elastic material, both are suitable, while for nonlinear elastic material as rock salt, the load control is not compatible to do the test. However, some difficulties have concerned to extracted core specimens, that lead to do the experiments with different (L/D) ratios, which apparently effect on the result, however, it has been plotted the Young modulus vs. (L/D), figure (4-23), this figure has shown the effect the (L/D) on Young modulus for two different temperatures, also for specimens which has been experienced to multi-tri-axial test.

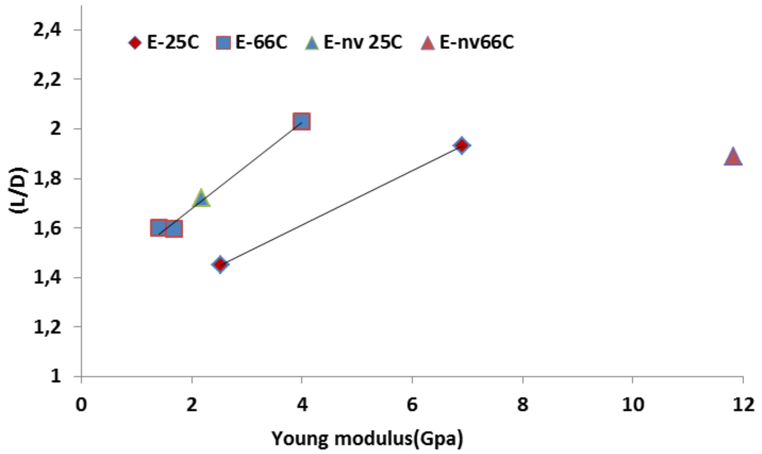


Figure 4-23 (Effect of L/D ration on Young modulus of Italian rock salt)

Laboratory tests for rock salt are being performed in many locations; one test was done to the Waste Isolation Pilot Plant (WIIP), which was designed for radioactive waste, in order to develop constitutive relations which can be used in structural design calculation and predication for long period term response of this repository and the local geological region.

Fig(4-24) has shown two hydrostatic loading curves ,the volumetric strains of specimen (7-2776) were computed as 3 times the axial strains $\epsilon 1$ while curves (7-2834.5) fits two sets of data ,(ϵ=3 ϵ1) and (ϵ=3 ϵ3), the agreement between two curves was good, which is meaning that the rock salt was mechanically isotropic prior to testing.

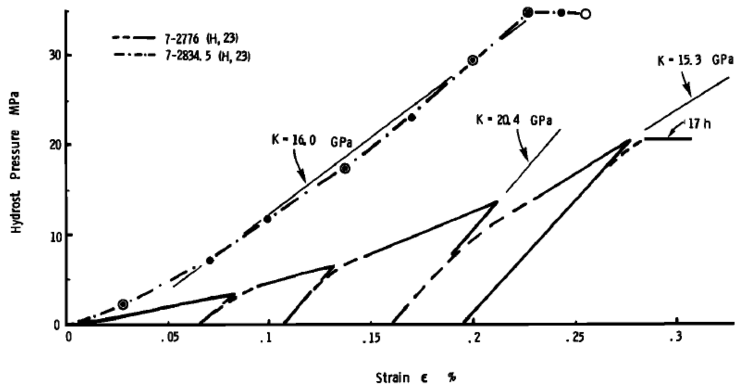


Figure 4-24 Pressure –volumetric strain curves for New Mexico rock salt subjected to hydrostatic compression at ambient temperature Open and solid circles identify data from linear measurements of ϵ1and ϵ2= ϵ3respectively (Warwersik et al,. 1980)

Furthermore, the figure has shown that the tangents for different unloading and loading parts of curve for this test and above for 6,9MPa the yielded bulk moduli K in range from 15 to 25GPa, while the elastic bulk modulus below 6.9 MPa is less than this range and approximately 10MPa, the most important observation on this figure are the non-linearity between loading and un loading in low pressure before reaching to value of in situ state ,this is specialized in rock salt because the closure of the cracking ,pore collapsed and grain boundary consolidation ,and all of these phenomena may be have gone on simultaneously as well these cracks remains closed during the period between unload /reload cycles.

This figure also has shown the net of consolidation which is somewhat time dependent, at range of pressures (20.7 to 34.5 MPa), the strains were being continuing in reductions for several hours.

The same behaviour has shown in figure (4-25), but in our case there was limitation in equipment's because, it was not reach to this stage, while the general behaviour is the same, and the range for the Italian rock salt (10-30) MPa.

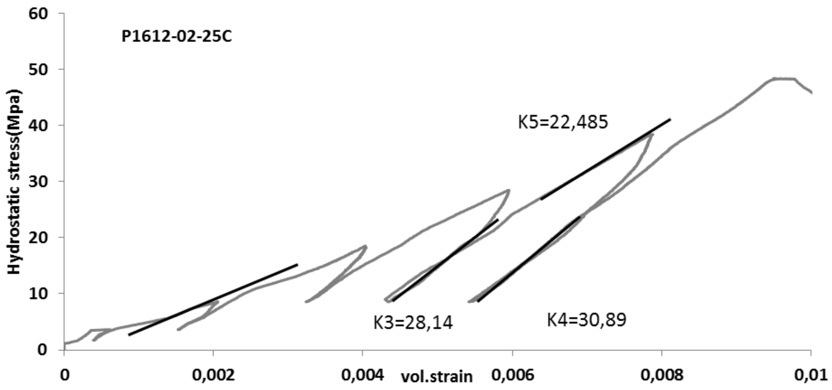


Figure 4-25 hydrostatic test for Italian rock salt at 25C

4.6.2. State of post failure

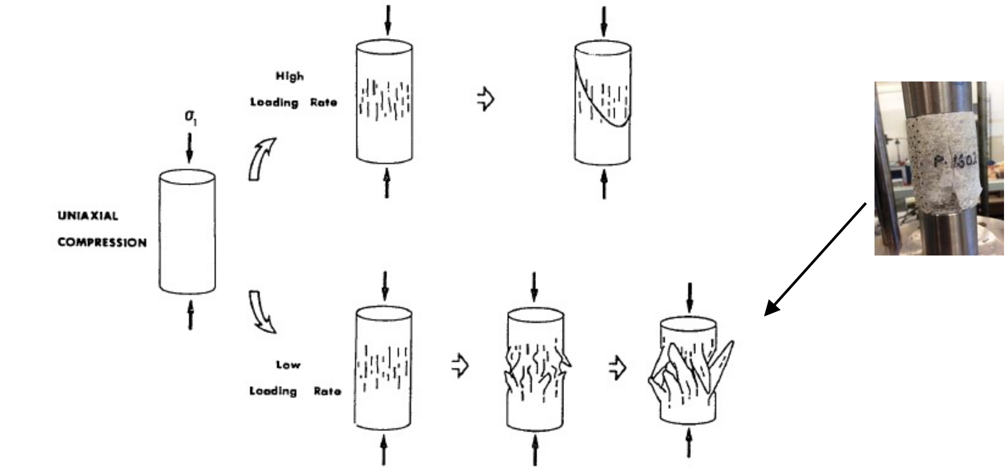
The mode of cracking, that would happen in the rock salt specimen when will be under UCT, for both high and low load. (Fuenkajorn et al,.1988).

This mode of specimen, was extracted by visual characterization after failure .it has been shown that strain rate and axial stress are the most important to control the mode of failure.

For instance in UCT, if the strain rate is so high (up to 10-4 s-1),the first crack in midsection of the specimen ,then these cracks will be developed to suddenly shear fracture, which appear after some changing in the color of specimen, because the refraction of the light ,

It was mention, that the normal to the fracture plane, make an angle of (60˚ ±2˚) (Fuenkajorn et al,.1988).

However, this failure mode will take another way, when the strain rate is low , it share the high strain rate behaviour in the first appearance of crack in the midsection, and change color from dark to light, but it will be different that this crack develop to just in vertical direction and will be extended without convert to shear fracture., at this state the strain-stress curve will be in the peak ., and generally the strain- softening behaviour in low strain rate .See figure(4-22). The schematic show how the strain rate effect for post failure mode.



Failure of uniaxial compression salt sample.

High loading rate: development of small vertical cracks, distinct shear fracture induced at an angle of 30° with the core axis.

Low loading rate: small vertical cracks; large vertical cracks and chipping of small salt fragments; large salt fragments chipped out (spalling) with shortening of salt samples.

Figure 4-26 schematic for uniaxial compressive failure mode (Fuenkajorn et al,.1988)

It can be followed the micro-fracture during uniaxial test by using acoustic tool, because the permeability increase if a specimen do not be confined and was under high stresses. The damage factor (D) can be calculated by using compressive longitude velocity before UCT test and during the stages of test.

The damage factor was extracted for the specimen P 1102-2 using compressive acoustic tools "mention before in figure (4-3)

However the figure gives us, clear view for the micro-cracking development, and it should be improve the experiments for temperature too.

4.6.3. Temperature effect on UCS

The compressive strength was used here, the peak strength value that would be reached in stress- strain curves. See figure (4-27).

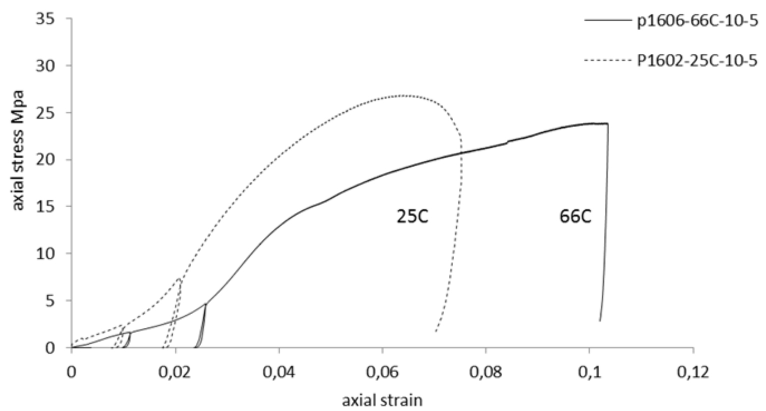


Figure 4-27 UCT of two Italian specimens for different temperatures under constant strain rate (10-5).

The figure has shown clearly the effect of compressive strength of Italian rock salt by decreasing (27.5 MPa) to (24 MPa) with high deformation reach to 0.1 compare with 0.06, it is approximated twice time to the room temperature test. The fact behind that, when the temperature increases, the deformation becomes more ductile as crystalline plasticity dominates intra-crystalline micro-cracking, which is clearly noticed, when confining pressure are very low.

Therefore at fixed shear strain, dilatant inelastic strains decrease at temperature increases, which mean that crystalline plasticity is more temperatures sensitive than is inter-crystalline micro-cracking, (Du et al,. 2012). (Senseny,. Et al,. 1992). it’s worthwhile, to compare the behaviour of Italian rock salt with other type of rock salt under the effect of temperature. It was chosen the Thailand rock salt for that. (Sriapai. et al,.2012). See figure (4-28).

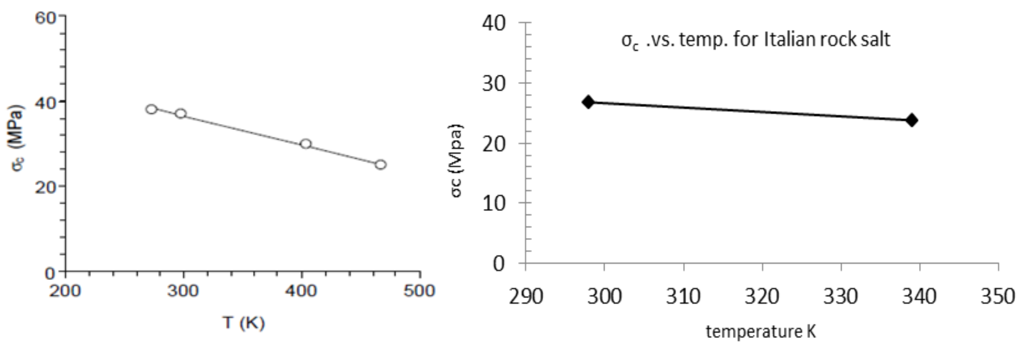


Figure 4-28 compressive strength vs. temperature for Thailand rock salt, and Italian salt.

The trend is not steeply, compared with the rock salt from Thailand for example; because the temperature gradient was not too big. There are some factors which were believed that, behind the decreasing in the strength when the temperature increases:

First, sometimes the rock salt has some different minerals which has different thermal expansion, also ,the anisotropy of anisotropic stratum layers this lead to different thermal expansion coefficients, as well strain energy which was stored between crystal give the possibility to defect, stripping, fracturing and residual thermal stress.

Second, these crystalline particles have considerable fracture will be thermally fragmented when, and it will be expanding freely under the influence of temperature.

Third pre-existing cracks, colloids and some unstable of evaporated minerals in the rock salt can cause decease for the strength.

Farther more, other comparison between Iraqi rock salt and Italian rock salt by USC test. However, the Iraqi rock salt was extracted from depth (2585) meter, while the Italian rock salt not too much than (200) meter but the compressive strength of Iraq rock salt (16 Mpa) is less than of Italian rock salt (27.5 MPa). See figure (4-29).

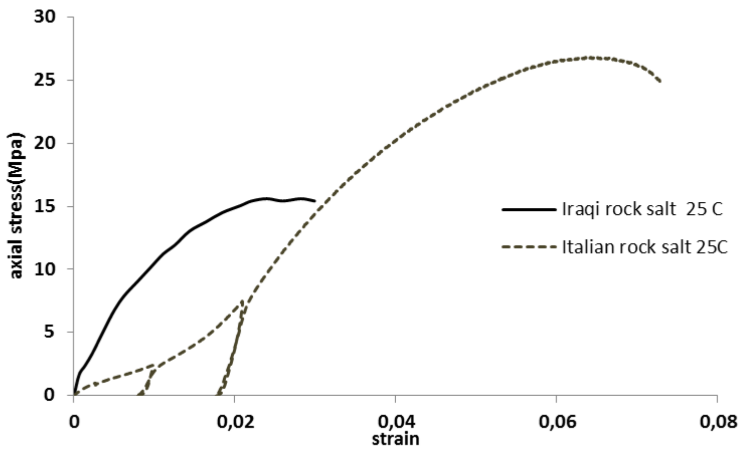


Figure 4-29 stress –strain curves of Italian and Iraqi rock salts.

4.6.4. Strain rate effect on UCT

In order to see the effect of strain rate on Italian rock salt, different experiments was done, it is seemed, if the strain rate changing (10^{-1}), do not have noticeable effect on UCT of the Italian rock salt, however this effect will be noticeable when the strain rate difference more than (10^{-2}) .See figure (4-30).

The figure has shown another example for the effect of strain rate during temperature (25C) on the uniaxial compressive strength; two strain rate ($2.4x10^{-5}$), and ($2.4x10^{-6}$) have been used . Its noticeable difference in the compressive strength, (30.95 MPa) and the other (26.79MPa), this difference might be returned to the fiber of each specimen. One of them has been shown viscoelastic behaviour in the beginning of the test, because the closing micro-fractures even the strain rate was being higher than the other comparing specimen. The energy that has been came by high strain rate, should be reserved in rocks, but it was consumed to close the naturally micro-fractures on the specimen.

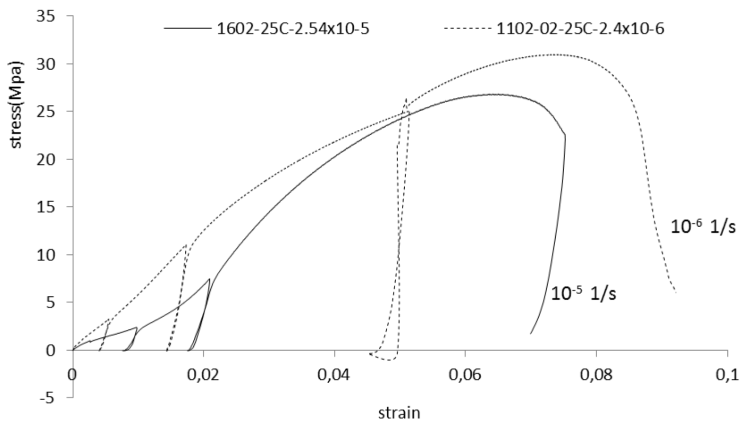


Figure 4-30 UCT for two strain rate of the Italian rock salt.

The other groups which have done under different strains with (66C).See figure (4-31). Here, two specimens have shown coinciding in behaviour under (10^{-6}), and one of them has shared the other rocks in the same behaviours, when increasing strain, the compressive strength increase too. However, other specimen has shown, less compressive strengths even the strain rate higher than the other.

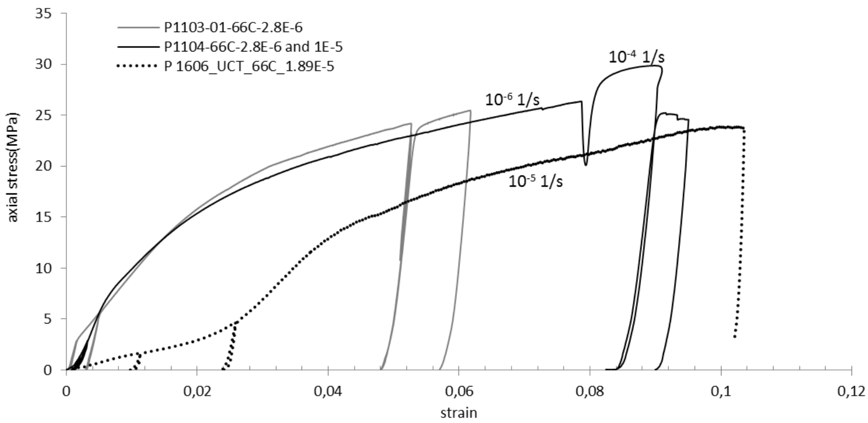


Figure 4-31 affect the strain rate on UCT.

General view of figure has shown changing when strain rate would be increased, (10^{-6}) to (10^{-4}), the effect it's clear that the compressive strength is increased , however, the other test which was done (10^{-5}),it has shown contrast behaviour, the general behaviour has been less than (10^{-6}). It may be the size of specimen effecting, because the compressive strength is not intrinsic property of rock. However, the intrinsic property does not depend on specimen geometry and loading conditions of the test, while compressive strength depends.

So the compressive strength is probably the most widely used and quoted rock engineering parameter and therefore it is crucial to understand its nature, from the engineering point of view, if the applied stresses reach to this value, there can be catastrophic consequences, but in rock engineering, when a rock reaching for this limit, does not mean, it is reaching for failure because there is retains some load bearing capacity in the post peak region.

Here, should mention to the effect of specimen size on the experiment, generally, if the length to diameter ratio is keeping constant while increasing the size, the compressive strength will be reduce ,because the increasing micro-cracking when increase the size. However, the Italian rock salt specimens were cut with different length to diameter ratio.

This behaviour was presented also by (Liang et al,. 2011), the peak strength of rock salt is little affected by strain rate, as in our case, rather than at the same strain rate, it was got less compressive strength, as it can see in the figure(4-32), farther more when strain rate was increased the compressive strength was decreased (see figure right)average value of the peak strength are

(12.29MPa,and 12.4MPa) at strain rate (10^{-3}) compare with (15.36MPa, and 12.49MPa) at strain rate (10^{-4}) see figure(left).

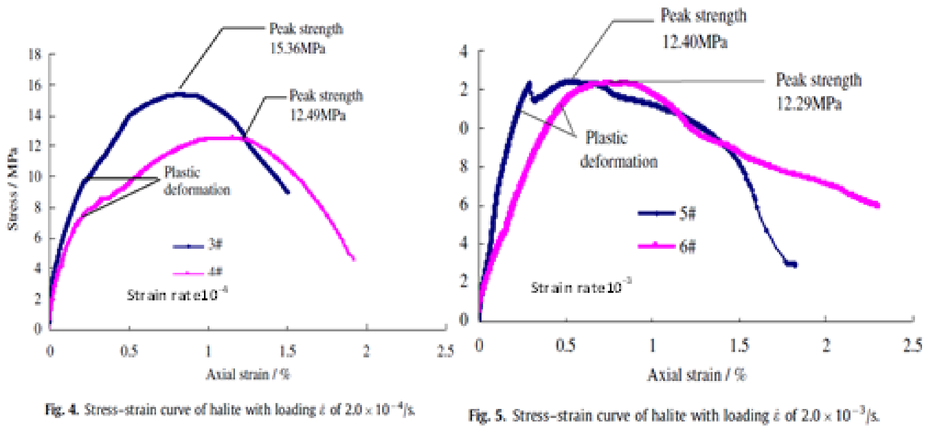


Figure 4-32 UCT with different strain rate for Jiangsu. China rock salt (Liang et al,. 2011)

The peak compressive strength of Italian salt has average value (25MPa-30 MPa) which is close to the value of the compressive strength of Paradox rock salt, as the comparison that was done. See figure (4-33)

While, UCS for Iraqi rock salt (15.6 MPa) is lower than the half UCS values for Italian rock salt, and the Jiangsu rock salt, that this rock salt was deposited and formed in different styles through different geological time.

Generally, the younger deposit salt should be weaker than oldest deposits, but the strain rate should be affecting the same on the strength, as it was reported (Farmer et al,. 1984) when the strain rate between ($5x10^{-3}$ to $2x10^{-4}$ 1/s) but for confining pressure (3.5,7,14,35,42 MPa),

Furthermore, the behaviour of rock salt under different strain rates, is completely differ from other brittle rocks as sandstone., as it was mention , that UCS of this rock increased from 64 to 75.1 and 99.5 MPa when increased strain rate from $2.5x10^{-1}$, to $2.5x10^{0}$ and to $2.5x10^{1}$ 1/s.

In addition for granite, which was tested under confining pressure, and for different strain rate, it was noticed that the compressive strength increased when increase strain rate, and this increasing would be less intensively when the confining pressure increasing. The rock salt is classified as soft rock, which was characterized by low UCS and very strong rheology properties, which can divided into elastic and visco-plastic deformation, which depend directly to the loading rate and confining pressure.

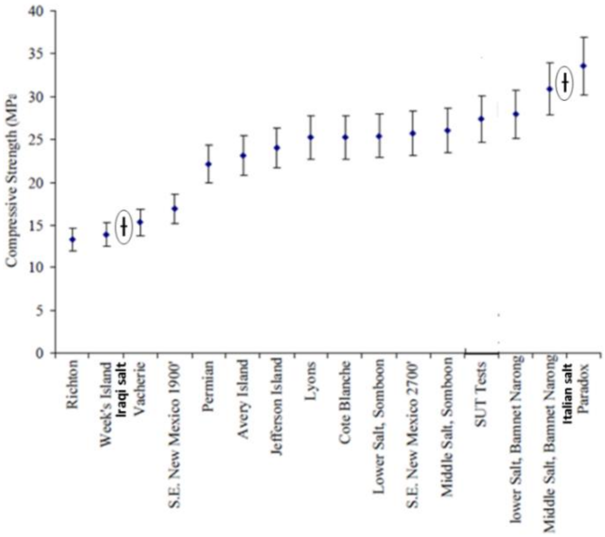


Figure 4-33 Italian and Iraqi rock salt plotted on comparison compressive strength vs. location (after Hansen etal.1984; Plookphol, 1987; Boontongloan, 2000; Fuenkajorn and Wetchasat, 2001).

So, in order to collect all uniaxial compression tests with different strain rate and for two temperatures (25C), and (66C), here, it has been plotted, the peak compression strength versus strain rate that was used in the experiment .see figure (4-34)

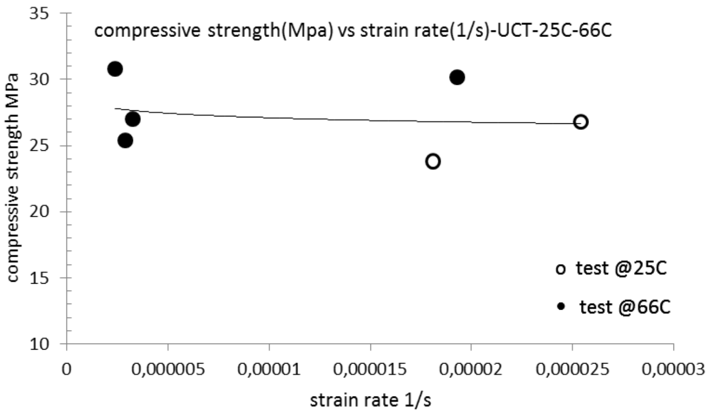


Figure 4-34 summarize UCT experiments.

In brief, the strength and deformation of all rocks are affected by loading rate, temperature, and moisture content and so on, as well rock salt; however it has typical properties of low strength and strong rheology.

4.6.5. Memory effect on experiments of rock salt

The best two methods which was used to evaluate the memory effect on rock salt, are acoustic emission (AE), known as the Kaiser Effect, and deformation memory effect.

The first shows rapid increase in (AE) count rate when the applied stress exceeds the first cycle stress load, while the deformation rate can be observed as inflection in the strain stress curve, when the 2nd applies cycle stress, is close to the first cycle stress load.

This effect was came because the development of irreversible micro-fracture in rock subjected to the first cycle, which was meant absence of crack growth and sliding processes (dislocation movement) at stress value less than the maximum value of previous applied load. (Filimonov et al,. 2001).When the 2^{nd} applied stress load will be reach to the previous value, the initiation processing of cracks and propagation will be start again.

It is very important to take this point in the laboratory investigation because all specimens of rock salt should be at least checked from the point of the in situ stresses condition that was extracted, as well the directions of these in situ stresses, because the rock was reserved in its' memories these stresses, that should be known, to do tri axial an uniaxial tests.

The procedure that was presented (Filimonov et al,. 2001), which were included 1st increase the hydrostatic load on the specimen for required confining pressure,2nd apply the axial load while keep the confining pressure, 3rd decrease the axial load to the confining pressure , 4th followed by remove the hydrostatic pressure from the specimen ,and finally applied uniaxial stress up to macro fracture, and there are not period of time between two cycles., as well here, the first cycle load do not reach for the maximum value for long time.

However, other specimen of rock salt has been tested by using two loading rate , (Senseny et al,. 1992) the rock salt has shown the sudden change of loading rate of confined specimen (3.7MPa) from10^{-6} to 10^{-4} and vice –versa. See figure (4-35).

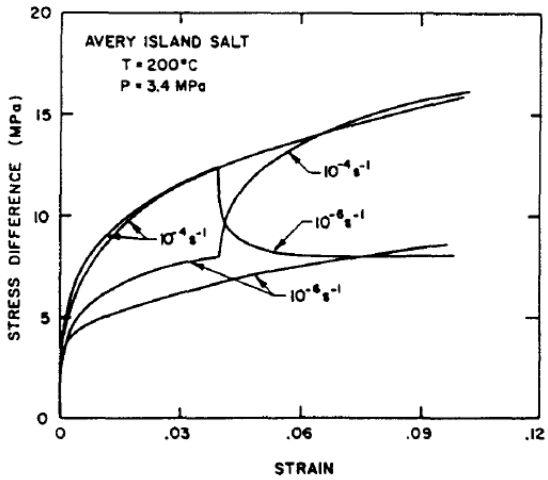


Figure 4-35 stress –strain curves from constant strain rate tests that involve sudden changes in strain rate (Senseny et al, 1992)

The history of rock salt might be included lot of factors, as loading rate, temperature and other. The inelastic deformation of the rock salt is time depends (very large strain rate), which can see it through creep test, when the rock salt will be under constant stress or in decay stress under constant strain rate in relaxation test. From the history point of view, the inelastic deformation of rock salt depends on thermo-mechanical history, as well as the current stress and temperature.

The rock salt are assumed, is memory fading, which clearly meaning, that the recent temperature and stress are effect directly on its' behaviour rather than far history. “This fading - memory postulate, is supported by the apparently unique relation among stress, strain rate and temperature for steady state creep. Transient deformation, however, is history dependent”.(Senseny et al ,.1992)

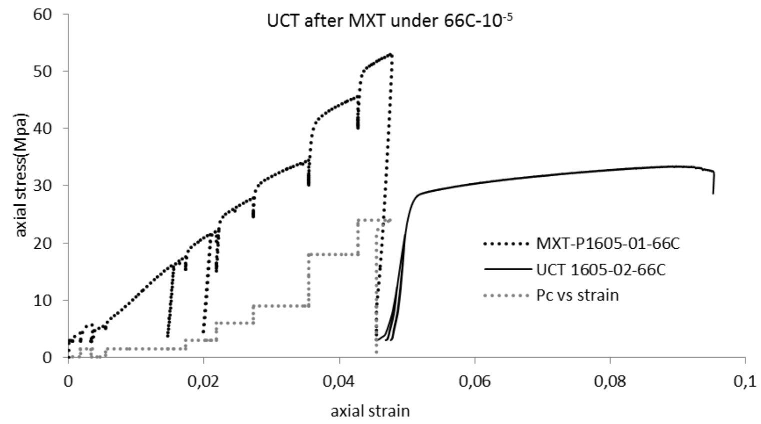
So ,the figure has shown behaviour of rock salt ,when the strain rate will decrease from 10^{-4} to 10^{-6} the stress- strain behaviour respond by decreasing in stress difference and completely forget the history that was on, its' " fading memory".

So, the memory affect summary, and because in our case studies, the memory or history play big role, because the borehole in oil well consist of different types of rocks, which have different pore pressures. This difference generates variance conditions, which represent memories.

Two types of the rock salt specimens which have used to show effect of memory, one of them have been under multi-axial test, while the other have been under uniaxial compressive test, both of these specimens have underwent to additional uniaxial compressive test.

So, general view of these two tests is being presented, and makes some comparison between them. It is very clear here, the specimen which has had under 1st cycle load (UCT), is less compaction than the other which has had in the 1st cycle load (MXT), which has the yielding 26 MPa and peak compressive strength is 34 MPa as well the strain at peak is 0.095 while the other specimen is 16MPa, 26 MPa and 0.17 respectively, the confining pressure has affected in MXT test. However, both of the tests have shown the history affecting. The period between two cycle of each test was (3) days

As well, both of them in the first cycle test have exceeded the elastic limits (Memory effect), the effect of irreversible deformation for 2nd specimen, that has stop at value of stress (25 Mpa), and, when it has reached of this value in the 2nd cycle, the specimen has shown anomalies or inflection .See figure (4-36), while the 1st specimen, it cannot find any anomalies.



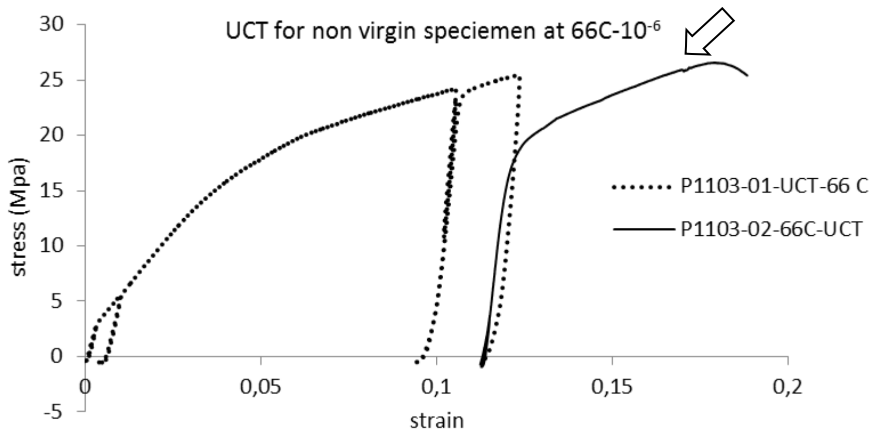


Figure 4-36 UCT (66C) for two specimens which have TXT and UCT history.

4.7. Standard triaxial compression test (STC),(MTC).

The target for most tri-axial tests is to get a failure surface. A series of tri-axial tests (a peak axial stress) are obtained for different confining pressures. Mohr space is the most criteria which are used to plot in 2D space the stress of stress. This space can give the cohesion and friction angle, as well the failure envelope for specified rock.

The procedure which generally is used for (STC), are followed the ASTM standard test method for compressive strength and elastic moduli of intact rock specimens (D7012-10).The axial load measurements, axial deformation and radial deformation should be recorded, furthermore, loading and unloading should be done to measure Young’s modulus and Poisson’s ratio (possible to do that through Uniaxial compressive test).

The strength and deformation characteristics for rocks, in particular rock salt; these parameters are important for design, construction and operation of structural engineering, (Wang. et al,.2013). Most of tri-axial tests are begun, in hydrostatic state, and then convert to tri-axial condition by changing laterals stresses, meaning axial and lateral stresses are not equal; it is classified under generally into three types:

- True tri-axial test.
- Tri axial extension test.
- Multi tri-axial compression test.
- Tri axial compression test.

The first is characterized by cubic specimen shape, as well the all stresses even the maximum horizontal stress are different from each other (axial and minimum horizontal stresses), while the second, the third, and the fourth test are connected with cylindrical specimen as well both horizontal stresses are the same, but the difference in way to apply the stresses, in compression the axial load are bigger than the confining pressure, while extensions tri-axial test the axial are lower than lateral pressure.

Generally, they were considered the important and famous in geo-material tests because it can discover mechanical properties of rock salt, as well study the other factors (temperatures, rate strain, loading rate, humidity,…..), the behaviour of rock salt under extension tri-axial test is less in 30% of the strength that is done in compression. (Lux et al,.2009)

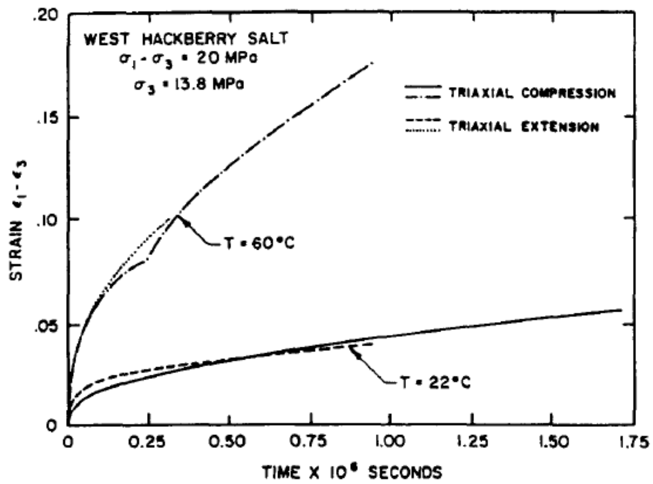


Figure 4-37 comparison of strain vs time curves obtained in tri-axial compression and tri-axial extension test.(Senseny et al 1992)

However, this difference between compression and extension tests, are so small. In the other word, the two tests have shown agreement.

See figure (4-37). It has shown, the effective strain –time curve is stress state independent, despite the experiments was done by two different ways (compression and extension) but here, it should be mention that the experiments have done under high devaitoric stress and confining pressure, which lead to stop micro-mechanics fractures and crystal plasticity dominated.

To discover the effect of strain rate companied with confining pressure under tri-axial test , A lot of experiments it should do to study effect of these variables on each other, and then on behaviour of rock salt , a good example for that the figure (4-38), which has shown the line “steady state flow” ,below this line a rock salt was being under steady state deformation without any failure, because as it can see, the strain rate is very low, for every stage of confining pressure, furthermore the temperature was fixed in the test., when the strain rate increased the rock salt crosses the this line, and it has shown failure in different strains rates.

However, the effect of increasing confining pressure has clearly appeared by widening a space for ductile deformation without any failure comparison with failure zone. , as well, when strain rate are increasing, the strength to failure increasing too for fixed confining pressure.

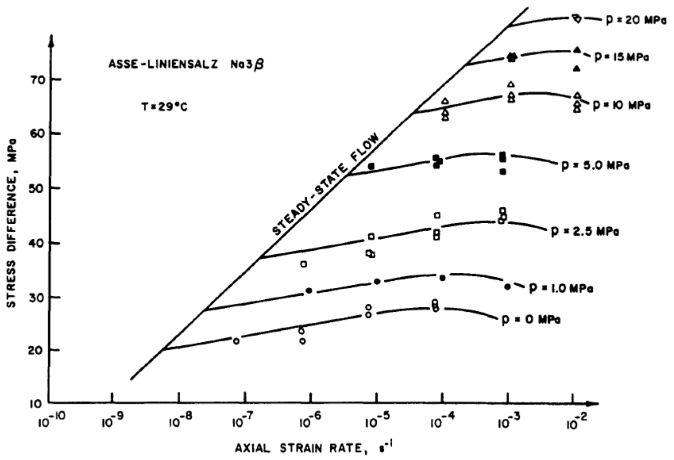


Figure 4-38 influence of confining pressure and strain rate on failure and brittle- to ductile transition in salt.(Senseny et al ,.1992)

4.7.1. Tri-axial compressive test processing.

Different methods have been shown (Bian. Et al, .2013), for triaxial compression test (Wang. et al, 2013), as well ASTM standard test method for compressive strength and elastic moduli of intact rock specimens (D7012-10),

- The domestic method.
- The Germany method.

The first method recommend to starting with confining pressure first ,then applying axial load with high speed, and give period of time to stabilized ,then control the axial load by the equivalent circumferential deformation when plastic deformation appeared, finally ,the testing processing was controlled by axial deformation at rate of 0.15 mm/min.

One the other hand, the Germany method, applying confining and axial load at the same time in order to reach with specimen for in situ condition, with less speed to reach for this value, and keep it for at least 24 hours, then reaching to the desired confining pressure, keep it constant and increase axial load by constant deformation rate (0.15%/min).

As it known, the successes test, should cover the influence of the initial damage- healing process ,when the stress will be beyond damage boundary that lead to increase permeability and decrease the strength ,because dialtancy phenomena and destruction the pore structure.

As well, when the low stress to strength ratio accompanied with high confining pressure, the healing boundary will be reached then the damages that was occurred will be healed again, farther more closed the pores and cracks, then reduction in permeability, so the domestic tri axial test will be without damage –healing deformation process, will lead to lower strength of rock salt than German test.

So it should be recover the initial damage in sampling process as much as possible before doing the tri-axial compression test. The figure (4-39) (domestic –left/ Germany –right), has shown the two methods

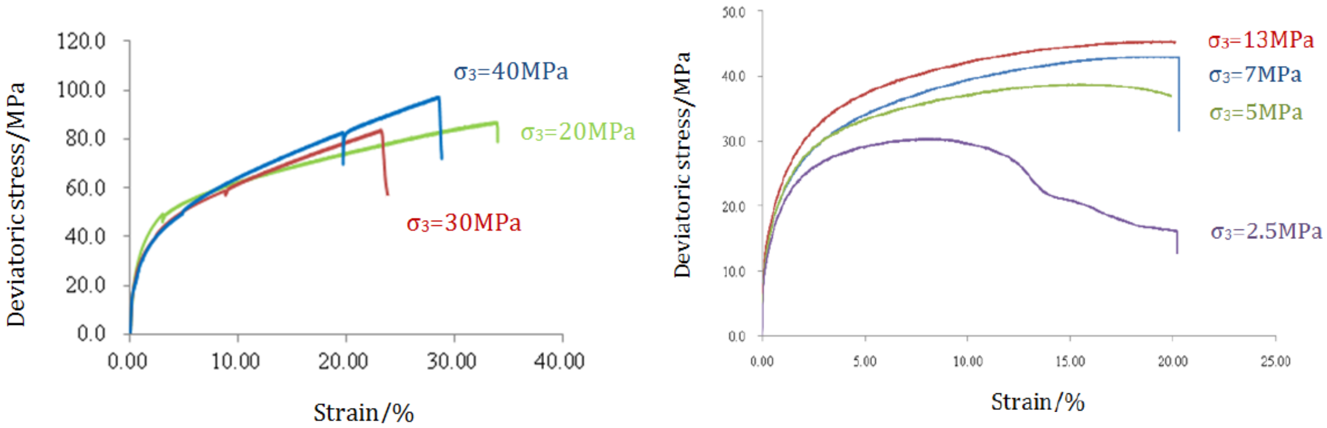


Figure 4-39 Deviatoric stress-axial strain curves of Jianghan and Jintan rock salt with different confining pressures (left –domestic method)(right –Germany method)(Wang. Et al,. 2013).

4.7.2. State of post failure

Most laboratory tests which have done through this chapter at $\sigma_2=\sigma_3$,which mean that for isotropic materials, the devaitoric stress (σ_1-σ_3) is related directly to the second devaitoric stress invariant(effective stress or Von Mises stress)($\sigma_e = \sqrt{3}.J_2 = \sigma_1 - \sigma_3$) and devaitoric strain, for $\sigma_2=\sigma_3$,the shear strain (ϵ_1-ϵ_3) ,which is directly relate to second deviatoric strain invariant as a general measure of shape changes. This assumption is reasonable and consistent with the observation that most salt cylinders retained their cylindrical shapes on average during deformations and local variations in deformations appear to be due to local textural and compositional inhomogeneity.

In the same extent, the effect of strain rate on the TXT is not identifying because most of TXT has been done in strain rate between (10^{-4} -10^{-5}) s^{-1}, but generally the physical characterization for the developed failure mode on the specimen was explained (Fuenkajorn. et al,1988), it was divided as follow:

- Dislocation of salt grains after applied constant strain rate in axial direction with constant confining pressure.(this dislocation occurs in the cylinder circumference at confining pressure more than 7 MPa)
- Bulging which developed to vertical cracks.
- Shear fracture with large bulging.

See the figure (4-40).

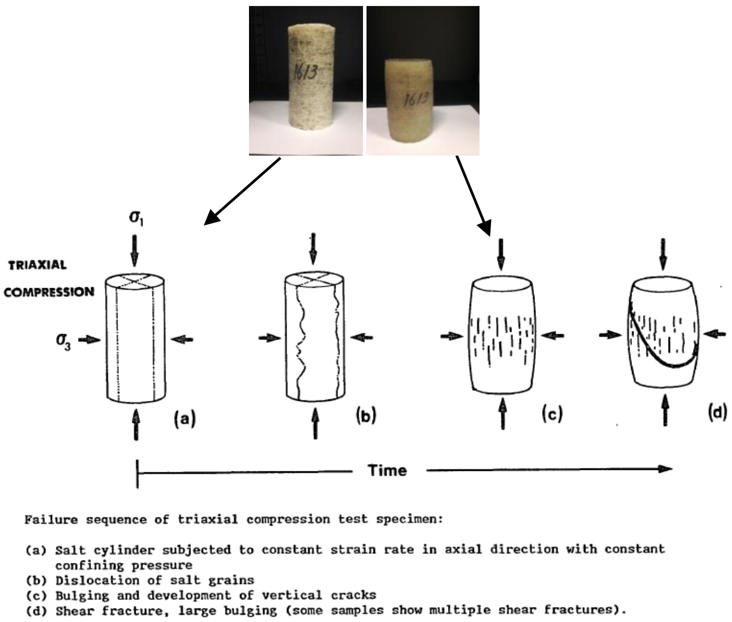


Figure 4-40 development failure mode in TXT (Fuenkajorn. et al,1988)

However, in MTX, it cannot see the bulging, then vertical cracks, because the value of confining pressure is so high, while it can see that in short creep test that was done (fixed axial stress, and decrease confining pressure, and keep it for short period of time), the specimen has shown case (C) (figure (4-40).

4.7.3. The compression tri-axial test results.

The main strain rate range for rock salt has been found in between (2×10^{-3} - 2×10^{-9}) s^{-1}. (Horseman et al,.1990), as it was mention that the German test loading strain rate of 0.15% /min ($2.5x10^{-5}$) and domestic test of 0.15 mm/min (about $1.25x10^{-5}$).

The strain rate for multistage tri axial tests that have done for Italian salt was in this range ($1.9x10^{-5}$ to $2x10^{-5}$ s^{-1}), as it can see in the figure (4-41).

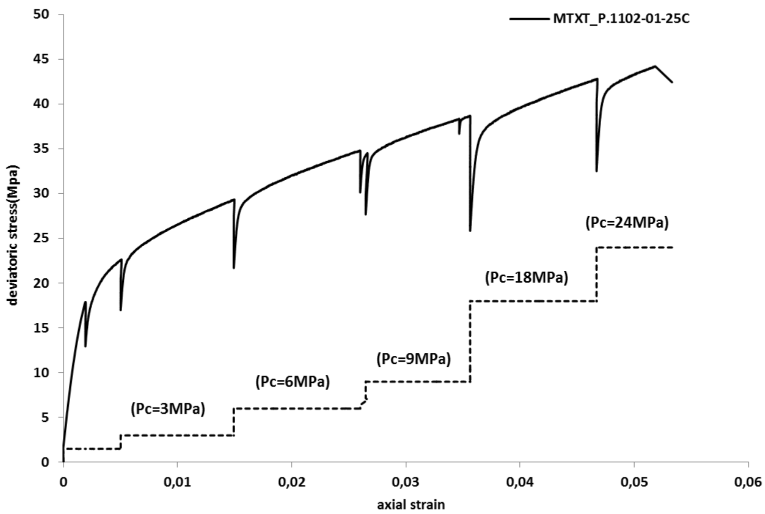


Figure 4-41 multistage tri axial test for Italian salt in room temperature

The figure has shown that, when increased the confining pressure, the strength will increase too, at fixed strain load rate, most rocks salt have shown this behaviour. The Italian rock salt has shared other rock salt this behaviour, for instance the Jianghan rock. One of the most characterized feature of the multistage tri-axial test, which is benefited from one specimen for multiple confining pressures for different deviatoric steps, for fixed strain rate.

So, it can use Mohr criterion to get angle friction angle (18.2˚) and cohesion of the Italian rock salt (8 Mpa) , and compare with Iraqi rock salt, which has angle friction angle (14.5˚) and cohesion (5.4MPa), and the results can be summarized in the figure (4-42).

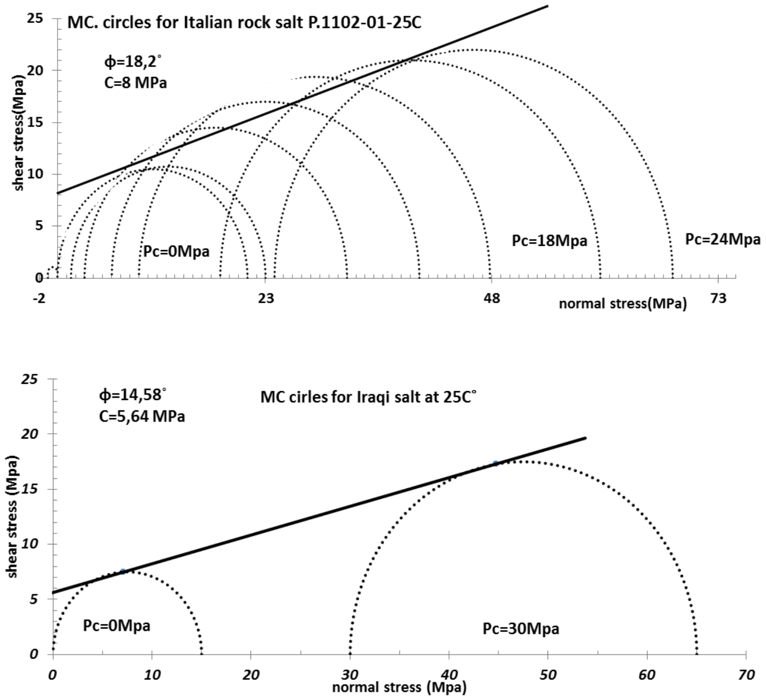


Figure 4-42 MC analysis for the Italian rock salt and the Iraqi rock salt at 25C°

It was analysed behaviour here by applying octahedral shear stress- mean stress space

It's possible to adopt the linear best fitting to calculating cohesion and the angle of internal friction according to (Lambe et al ,.1991).

$p= (\sigma_1+ \sigma_{3)}/2$ ………………….. (4-4).

$q= (\sigma_{1-} \sigma_{3)}/2$ ……………..……. (4-5).

$q=\psi p+d$ ……………………….. (4-6).

ϕ=arcsine ($\tan \psi$) ………….…. (4-7).

$C=d/ \cos \phi$ ……………………..… (4-8).

The results of using (lambe and Whitman method)(Lambe et al,.1991) ,can be seen in the figure (4-43), this method predicate the angle of friction angle is less than Mohr criterion, while the cohesion is bigger for both Italian and Iraq rock salt.

The failure envelop was plotted by using the tri-axial test data at (25C˚), and by using octahedral shear stress- mean stress space for both the Italian rock salt and the Iraqi rock salt . See the figure (4-44).

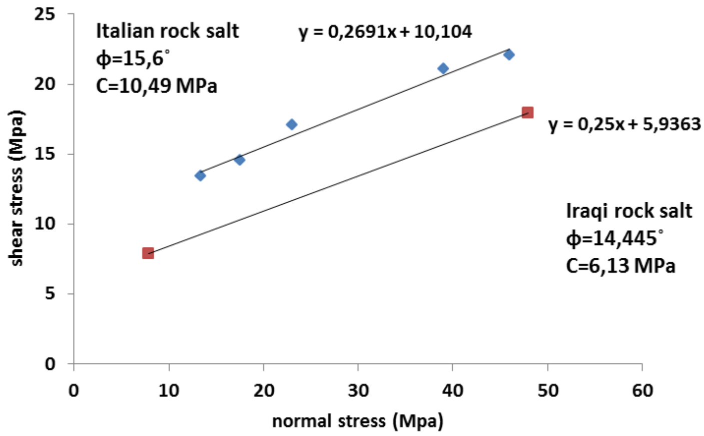


Figure 4-43 (Lambe &Whitman) method to calculate angle of friction and cohesion

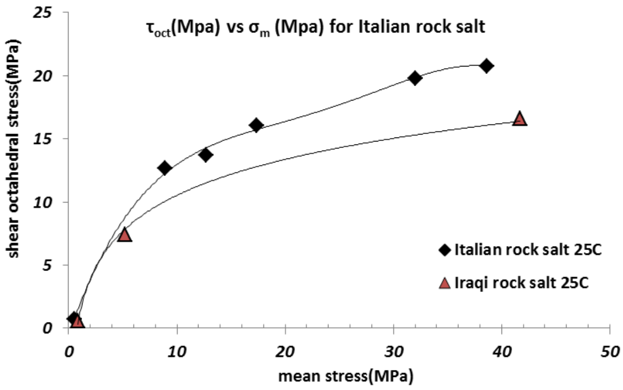


Figure 4-44 octahedral stress vs. mean stress for Italian rock salt

The failure envelope was done for both the Italian rock salt and Iraqi rock salt by applying the Hook Brown criterion, with parameters .($\boldsymbol{\sigma}$**c**=28,**mi**=6.513,**mb**=6.83,**s**=0.22,**a**=0.3),($\boldsymbol{\sigma}$**c**=15,**mi**=2.2,**mb**=3,**s**=1,**a**=0.3).. See figure (4-45), it's seem that the Iraqi rock salt weaker than the Italian rock salt, despite the less experimental points for it.

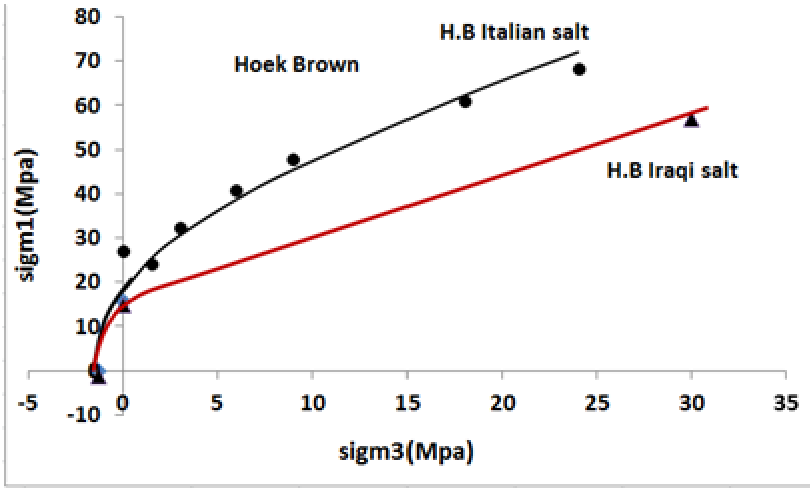


Figure 4-45 Hoek Brown curves for both the Italian and the Iraqi rock salts.

4.7.4. Temperature and tri-axial test

4.7.4.1 Temperature effects on general behaviour

The published experiments have been used for comparison the behaviour of the Italian rock salt, with the other rocks salt, in specified, the bench scale experiments , because , these experiments cover the case study, and simulate all related variables, temperature, pressure, humidity…etc.

So, to study the temperature factor effect, that is need to modified state of the laboratories equipment's to be able to do a test with this factor.

The temperature belts have used that connected with voltage regulator, and log data system which have directly gotten the data from thermocouples. See figure (4-46). This method has covered most tests that simulate temperature variable .

Figure 4-46 tri-axial cell equipment's with temperature bands, and thermocouples

The temperature effect has been taken wide space by researchers because the drastic effect on deformation and strength of rock salt. The range of degree temperature more than (150 C˚) has been covered, but here, the range has covered is (45-66) C˚. The range of the temperature extended between (26-70) C, are studied the on mechanical properties of rock salt in short term condition for uniaxial and tri axial test (Du. et al,.2012).See figure (4-47)

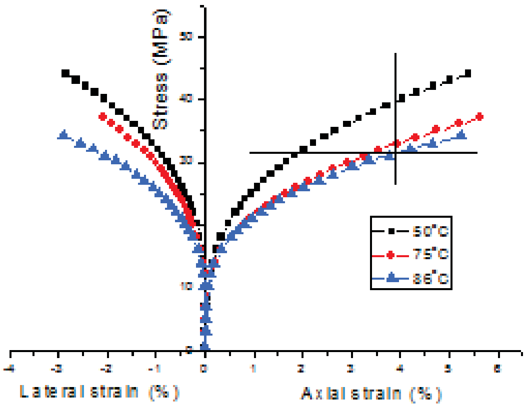


Figure 4-47 axial stress, axial strain, and lateral strain during tri axial tests at three different temperatures for confining pressure (20MPa)(Du. et al,.2012)

The general trend of rock salt behaviour has discovered by the multistage tri-axial tests to study temperature effect and confining pressure, for three temperature points (25,46, 66)C˚, because, most of Iraqi cases studies happened in this range of temperatures.

The experiments which was done in this range, are less comparison with those in high temperatures , because it was thought that below temperature 50C˚ there was not significant effect on the behaviour of rock salt(Senseny et al,. 1992), however the recent results has shown the effect of temperature at 46 C which decrease the strength of rock salt. See figure (4-48), it is clear the effect of temperature decreasing the strength of rock salt.

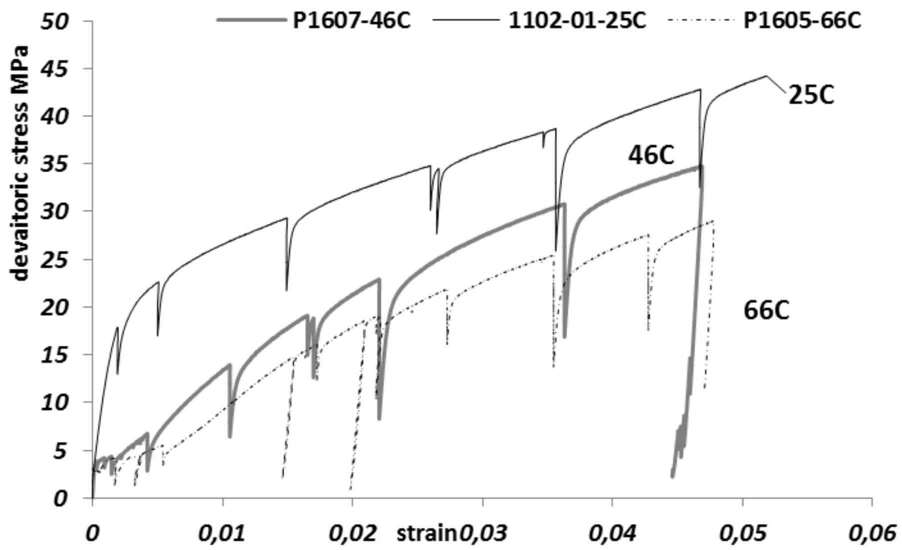


Figure 4-48 multistage tri-axial test with range of temperature (25-46-66) C˚ on Italian salt

To study the effect of temperature on the failure surface, the Hook Brown analysis for three types of tests have done. See figure (4-49).

The hook brown failure surfaces based on three tests have shown temperature effect. The strength at failure of rock salt have generally decreased, when the temperature increase.

Furthermore, the temperature has effectively affected when the confining pressure (9 MPa) for two tests (45, 66) C, while at confining pressure (< 2 Mpa), there are not shown any effect of temperature. The figure has shown that the maximum shear stresses at failure have decreased, 22.5 MPa, 17.5MPa then

14.5 MPa when the temperature has changed 25C˚, 46 C˚ and 66 C˚ respectively.

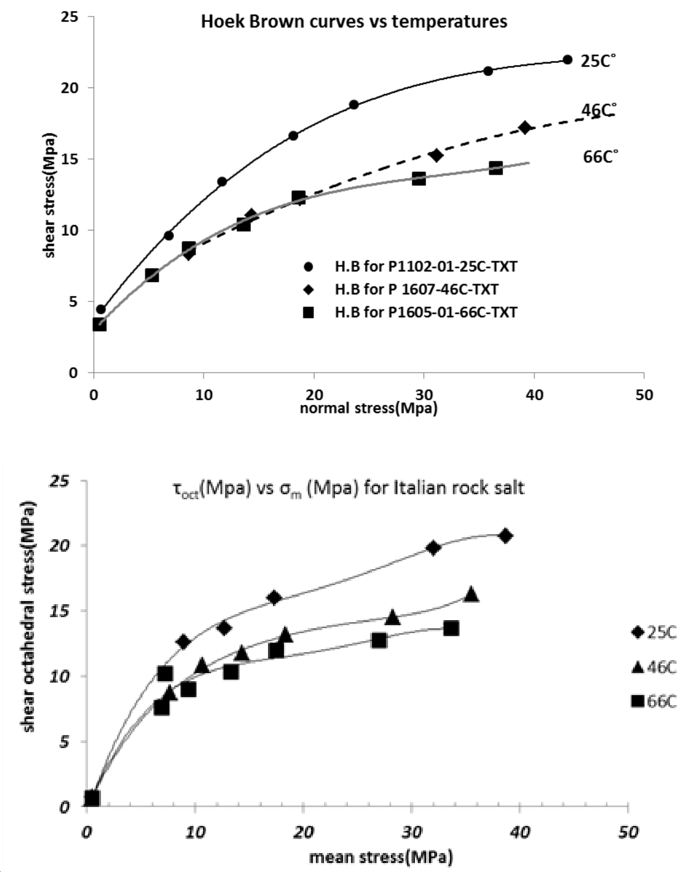


Figure 4-49 upper, Hook Brown curves for three TXM test with different temperature (25, 46, 66) C˚, and below octahedral shear stress vs. Mean stress space

4.7.4.2 Temperature effect on elastic properties'

When the temperature increases, that will effect on micro-crack which will grow continuously because the thermal damage, that leads easily to lateral deformation rather than axial strain, so it is noticed that the Poisson ration increases noticeably when the rock salt heated, because the heating creates internal thermal stress, and then failure will be produced (Du et al,.2012), see figure (4-50)

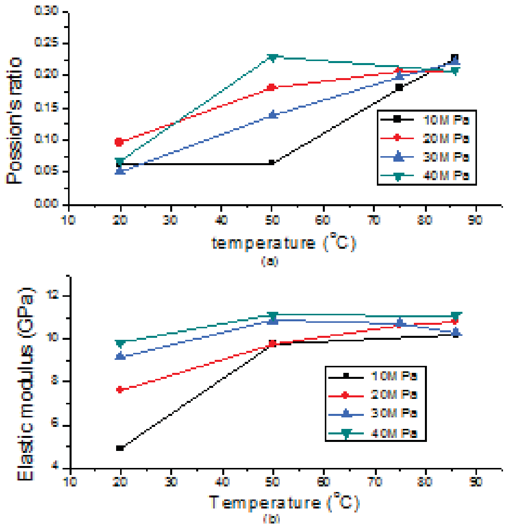


Figure 4-50 Poisson ratio and elastic modulus at different temperatures and confining pressures. (Du et al,.2012)

On the other hand, the Poisson ratio has not affected by temperature, as it was mentioned by published articles (Sriapai. et al,. 2012), (Senseny. Et al,. 1992) See in figure (4-51). So, the effect of temperatures on the Poisson ration has not been shown the same behaviour, the reason behind that might be the impurities and micro-structural inside the rock salt.

However, most of published articles have approximately agreed, that the other elasticity coefficients, will decrease when temperature increase, as it has shown in the figure (4-52)

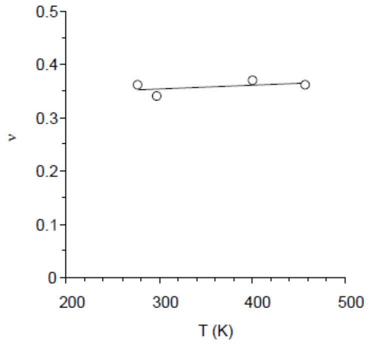


Figure 4-51 the effect of temperature on Poisson ratio (Sriapai. et al,. 2012)

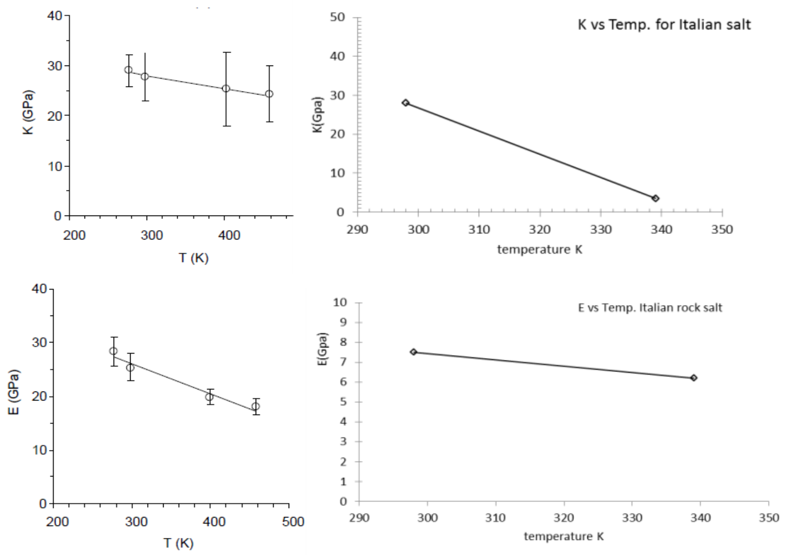


Figure 4-52 comparison between the Thailand and for Italian rock salt in effecting of temperature on the Elastic modulus and bulk modulus (K) vs temperature for literature (Sriapai. et al,. 2012).

4.8. Constant mean stress test.

This test is very important for the rheological models, because most geomaterials have shown a compressibility / dilative behaviour, which help to distinguish creep processes, in order to know which domain that a conditions of the stress of state. The volumetric strain and creep processes play important role for detection.

A direct way to get this boundary(compressive /delatancy), is by using true tri-axial test, which gives the space to perform different mean stresses and recording volumetric strain data, it can be achieved one test to one fixed mean stress value for different devaiatroic stresses,

As well, it should keep the elastic part of volumetric strain at constant level, however, the changing of volume strain is due to irreversible strain,but it can do this test in classical tri-axial method.

4.8.1. Processing of CMS

All three tests have achieved, the axial stress has increased and at the same time, the confining pressure decreased, in rate which produces constant mean stress. The main target of these tests is to determine the dilatation characters (the expansion in volume of specimen because micro-fracturing).

The methods was explained and described (Mellegard et al,. 1999), it was recommended that the increasing in axial stress rate, is twice of decrease in confining pressure till the fails of the specimen or the confining pressure will be zero.

When it will be kept the mean stress constant that is meant keeping the volumetric strain constant, or small accepted changes due a small level of compaction at low moderate stress differences, which mean there are not dilatant , while when reaching to the boundary of dilating, accelerating rate in volumetric strain , and change in its' direction(negative). This changing in volumetric strain mean the specimen was damaged by micro-fracturing.

4.8.2. Analysis the results

The experimental results that were done, despite their small number but are satisfied to get a good comparison with the famous dilatant criterion (Van Sambeek et al,.1993). This is a common method to develop such a relationship by:

- Transfer the dilatant stress difference value for predefined mean stress in term of invariants.
- Fitting experimental data to get mathematical model related to stress invariants

The first invariant of Cauchy stress tensor, I_1, and the second invariant of deviatoric stress tensor, J_2. The relations that connect those invariants with tri-axial compressive test data are:

$\boldsymbol{I_1 = 3\sigma_m = \sigma_1 + 2\sigma_2}$ .... **(4-9).**

$\sqrt{J_2} = \Delta\sigma/\sqrt{3} = (\sigma - \sigma)/\sqrt{3}$ …………………………………… (4-10).

So, the three constant mean stress tests have done, and the dilatant stress was extracted from plotting local volumetric strain and vertical axial strain vs. deviatoric stress. See figures (4-53).

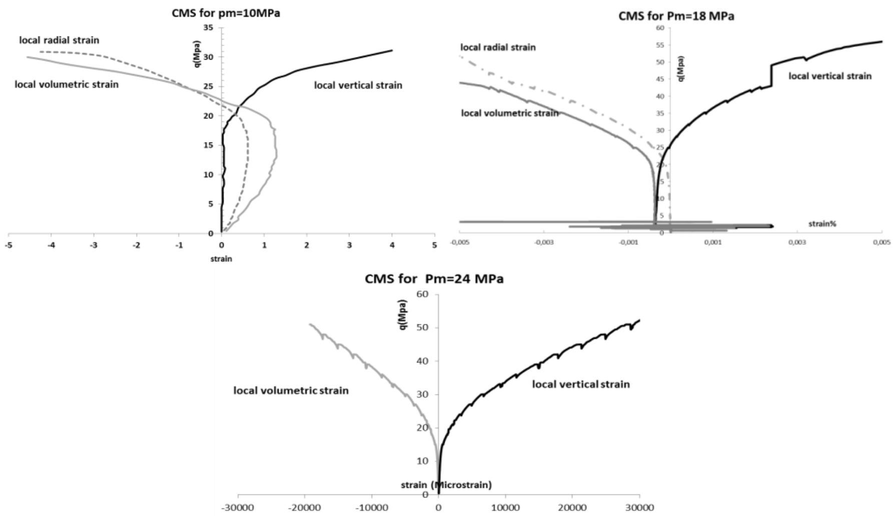


Figure 4-53 CMS test for Italian rock salt for three mean stresses (10, 18, 24) MPa.

The space that was created is between (√ J2 -I1), this relationship is linear, however it might be non-linear, but generally the boundary is separated the behaviour of rock salt into two regions, compressible region and other dilatant, while the boundary itself represents not volume changes. Actually, three constant compressive stress selected are, (10, 18, and 24) Mpa, and they have compared with Van sambeek criterion. See figure (4-54).

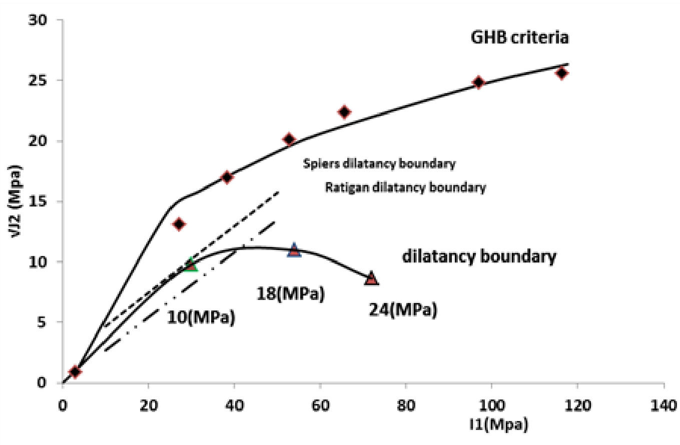


Figure 4-54 Spiers and Ratigan (Van Sambeek) criterion compare with experimental CMS data for three (σm) (10MPa, 18MPa, 24MPa) of Italian salt.

It can be considered the three tests are good, by comparison with other tests of rock salt. For instance, The CMT test was done for rock salt of Bay Gas Caverns at the McIntosh Dome (USA). See figure (4-55) (Devries et al,. 2002)

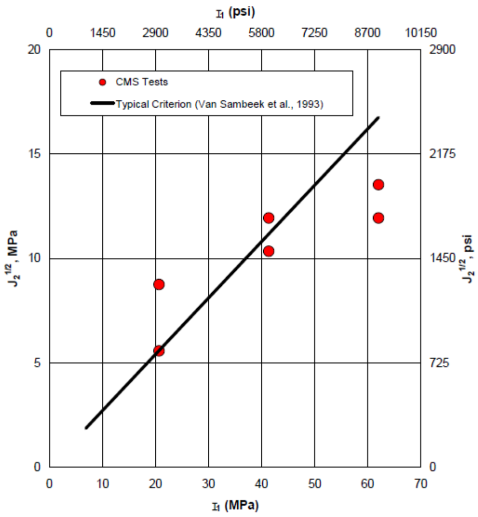


Figure 4-55 Dilation Criterion for McIntosh Dome (USA) rock salt.(Devries et al,. 2002)

It can be used the damage factor number by using the first invariant and second deviatoric stress, to check whether the rock under dilatancy or not. (Van Sambeek et al, .1993)

D= √ J_2/0.27I_1 .... (4-11)

The results for three tests can be seen in figure (4-56).when the value of this factor more than 1, which meant the shear stress in a rock salt ,is more than mean stress, that reflect, the domination of the dilatant behaviour , and that is clear, for all three tests, just one test was located in area of dilatancy region while the other two tests are located below the dilatancy boundary, so, one damage factor value (1.2), and the two others below (0.8)

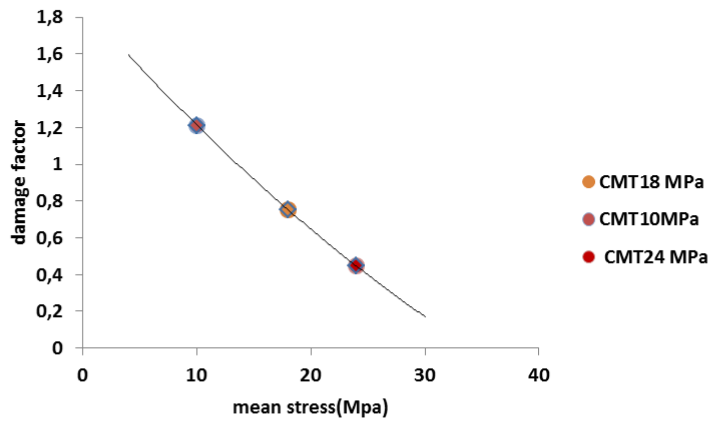


Figure 4-56 damage factor for three tests of Italian rock salt.

It can define the dilatancy ,as the point when the derivative of volumetric strain curve reach to zero ,and a further increase in deviatoric stress will cause the sample volume increase, which is represented the crack damage threshold (Compression /dilatancy boundary) (Alkan et al,.2007).

This parameter is considered very important for any geometrical structural, because it can be described the development of micro-cracks (Peach et al ,.1996) (Popp et al,. 2000)(Schulze et al,.2001)(Stormont et al,.1993)(Khaledi et al,.2013).The most indicated parameters for the dilatancy are, increasing permeability, increasing damage and the potential for creep failure.

It can be investigated the healing process from constant mean stress test, by return back to the hydrostatic part from the test, where the volumetric strain should be monitored .

Finally the macro view of the all tests before and after tests can be seen figure (4-57).

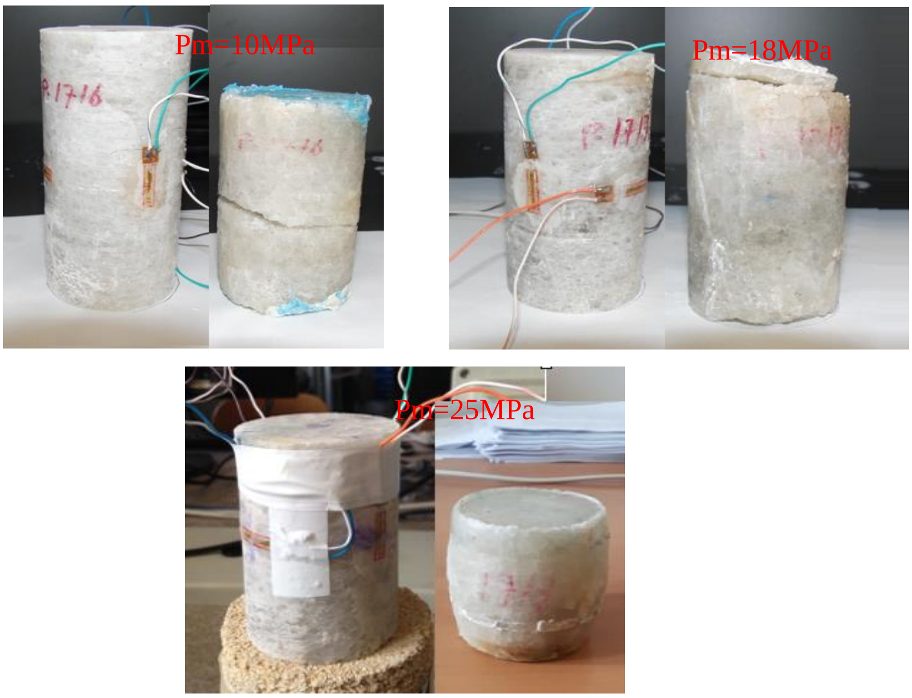


Figure 4-57 three constant mean stresses tests specimens before and after for (10, 18 and 25) MPa

4.9. Creep tests

The main target for most creep tests is to investigate the deformation of rock salt below the failure by subjected the specimen of rock salt to constant stress (differential stresses).

It's a time-dependent test, under constant stress, most of rocks show some creep but, Crystalline rocks are characterized by creeping as rock salt.

The creep strain seldom can be recovered fully when loads are removed, so thus it is largely plastic deformation. Generally, there are three different types of creeps which have the rock salt characterized, primary (transient), secondary (steady state) and tertiary (accelerating leading to failure) strains, of course after elastic strain; see figure (4-58).

The shape of the curve result from two competing fundamental processes, hardening and recovery, when applies stress or change a load, the strain is changed to transient creep, when hardening control on recovery, and, if the equilibrium between those processes will be done, the rock salt change to steady state creep.

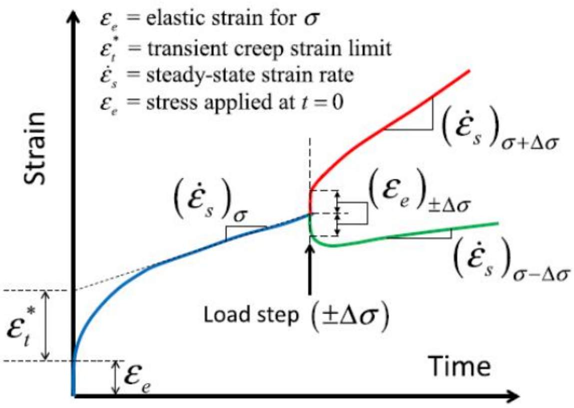


Figure 4-58 three types standard of creep in rock salt

4.9.1. Laboratory creep testing devices

There are different types of creep apparatuses of rock salt, but generally it can be classified into two parts:

- Cantilever creep apparatuses.
- Load /displacement controlled apparatus

  See figure (4-59).

Under these two types of tests, the creep test can be subdivided depending on the way to apply the constant loads (Uniaxial creep test, tri-axial creep test). Both of them discover the behaviour of rock salt under constant differential stress to extract the parameters that use in predicted constitutive models. Here, it has been investigated the behaviour of the Italian rock salt under uniaxial stress and for long period (more than 6th months); on the other hand, short period creep tests have done too.

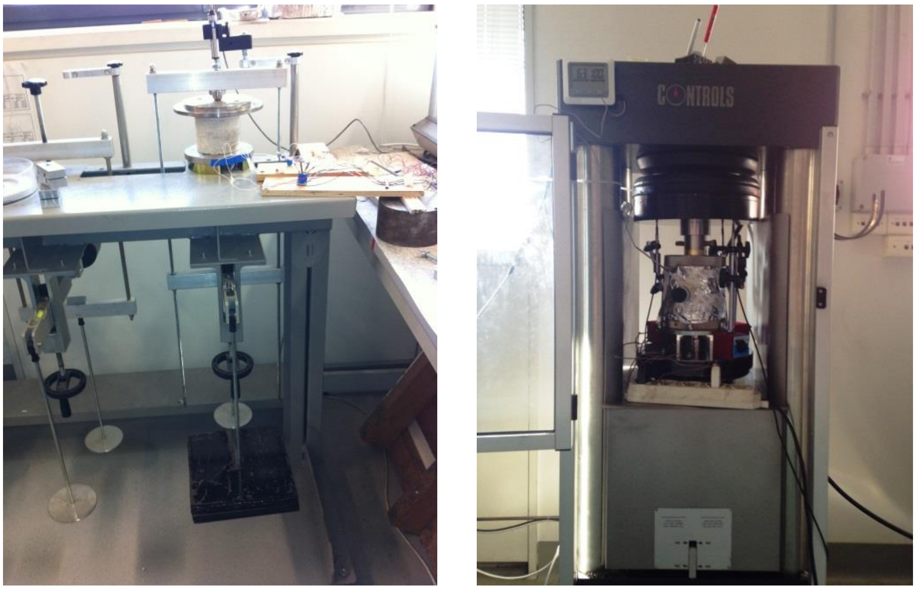


Figure 4-59 cantilever and load/ displacement controlled apparatuses for long and short creep tests.

4.9.2. Cantilever creep tests

Different types of apparatuses which are used depending on the type of tests, and to benefit from the facilities. Consolidation bench frame for tri-axial tests (28-T-493. 600 KG Max load) have used for elementary long term tests.

Two sizes of the Italian salt rocks have been used (38mm, 54mm), (uniaxial compression creep test, uniaxial extension creep test) respectively. On the other hand, short term tests, tri-axial compression creep test was done by using Hook cell apparatus, that give the ability to reach with confining pressure to (48 MPa)but for short term.

The elementary uniaxial compression and extension tests have done by multistage loads (0.68, 1.5, 2.4, 3.26, 3.6, 4.46 and 5.32) MPa, for uniaxial compression creep test and (0.25, 0.513, 0.6, 0.68, 0.72, and 0.81) MPa for uniaxial extension creep test.

The Uniaxial creep test was done by using simple and light weight frame, LVDT was used to measure axial strain , while strain gauges were used to measure local axial and radial strain .

4.9.2.1 Elementary uniaxial compression test (Italian salt)

Despite the tests have considered as elementary for light weight frame because the loads limitations, however the nature of rock salt is to creep even with low stress and room temperature, so the results are good. The test has done for multi stage loads for every three periods; the general trend of creep for these periods can be seen in the figure (4-60), which has divided by quick unloading-loading period. In order to see the details of general trend of the creeping for this test, it has plotted the axial strain vs. stresses for the first period, and strain rate vs. time to see the behaviour of this period clearly. See the figure (4-61-a);

The specimen has loaded till 3.26 MPa during (6.2 days); the rock salt has been shown transient creep and it was reached to stationary creep after 2 days with load reach to 1.5 MPa, and despite the period was very short compare with other two periods, but the behaviour of rock salt specimen, seem typical, because after elastic and transient creep, and then stationary creep have clearly shown despite the short period, comparing with long period of time.

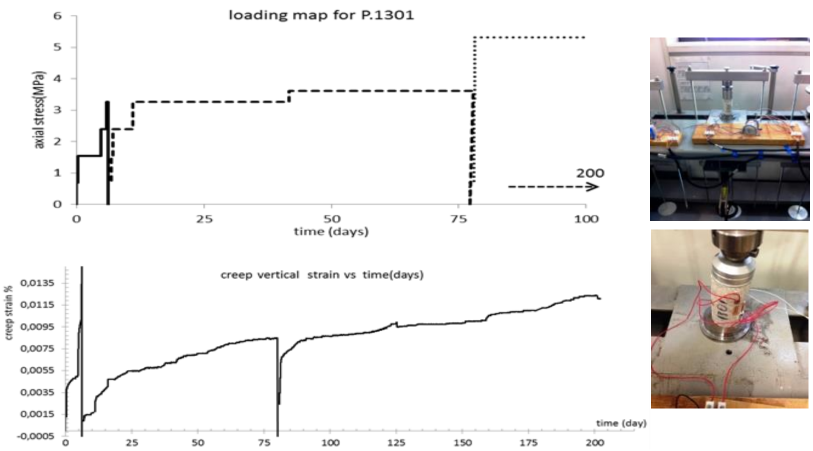


Figure 4-60 long term creep test (vertical strain), with loading map for P1301 Italian salt

The loading rate has effect, in specify the first period, which has applied the same distribution loads for two long period to this period .Furthermore, the two longest period, the rock salt specimen has exposed for many factors (temperature, humidity) because the time, compare with the first period. In addition, despite the different in loads between the first and third loads (3.2 Mpa)(5.3 Mpa), the maximum obtained strain of the first period (0.0125%), is the same of the end of the test for the two longest periods.

The Italian rock salt specimen has shown transient deformation for each longest periods, ($3x10^{-9}$ 1/s) for the second periods and has gradually decreased till steady state strain rate (1.5 $x10^{-9}$ 1/s), while for the third last period has shown transient strain rate ($7x10^{-9}$1/s) and steady stage rate ($1x10^{-10}$ 1/s) at (175) days, when the steady state creep has controlled .See the figure (4-61-b).

However, the Italian rock salt has shown in the first period of loading which extended (6 days) transient and steady state creep, its' (10^{-6} s^{-1}), which has reached after (3 days), because the loading rate are so quick compare with the other two periods, while it has shown transient creep during period extending (145 days), for 2nd and 3rd loading test, and finally it has reached to steady state creep (10^{-8} s^{-1}).So, all period have shown the general trend strain rate starting by (10^{-6} 1/s) transient strain ,and reached to (10^{-10} 1/s) steady state starin.

Actually, for comparison, the range of strain rates for in situ deformation of rock salt is extended between (10^{-8} s^{-1}) to (10^{-16} s^{-1}), (Jackson et al 1986), so the Italian rock salt has shown strain rate to this range. For the first period, it has shown considerable strain rate, which was considered high strain rate if, it compare with most borehole closure during accelerating creep (10^{-8} s^{-1}), as well in mine closure extended between (10^{-9} s^{-1}) to (10^{-11} s^{-1}).

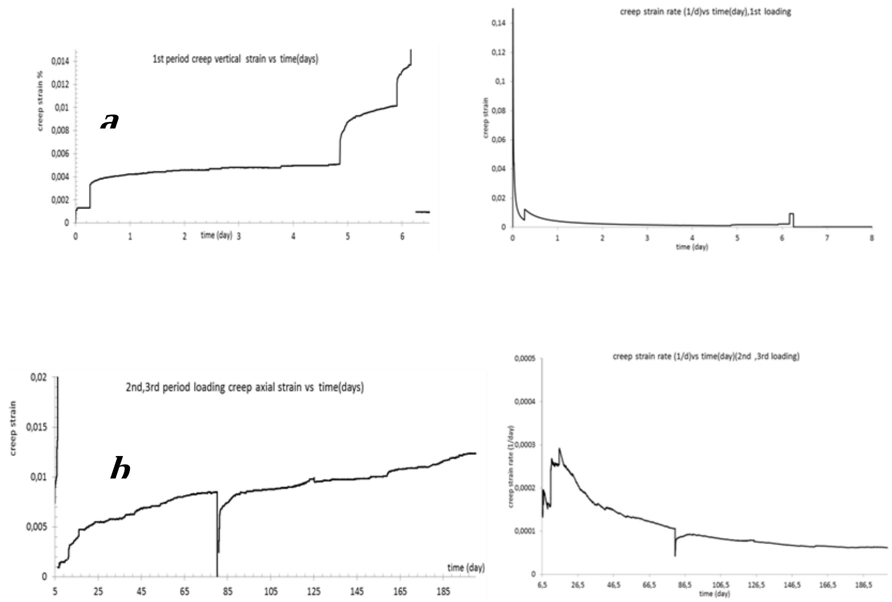


Figure 4-61 axial strain rate vs time for long term creep test of P1301. (Italian salt) 1st, 2nd and 3rd loading

On the other hand, the ASTM standard methods specify that to minimize the effect of grain size of a sample diameter should be at least ten times the average grain size of the rock salt, for Italian rock salt, the average grain size equal to (3mm), so the diameter of the specimen is compatible with ASTM.

Furthermore, despite all limitations, the radial deformation has recorded during this long term test, and then calculate Poisson ration with time, however the loading is not big enough, so the maximum value was reached (0.32) during 100 days. See figure (4-62).

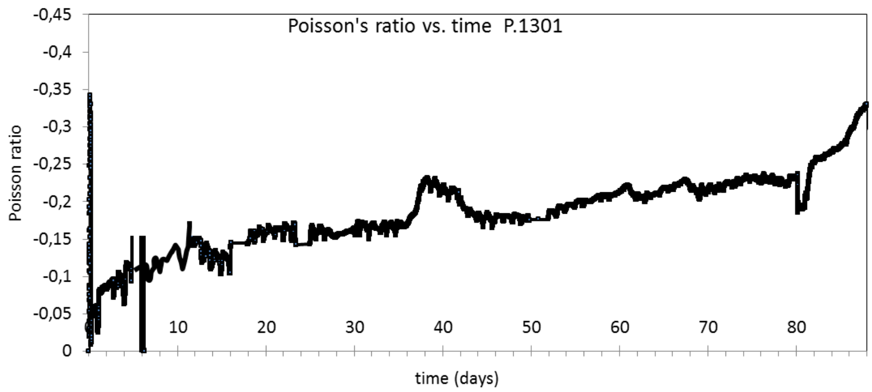


Figure 4-62 Poisson ratio vs. time of the Italian salt (P.1301)

4.9.2.2 Elementary uniaxial compression test (Iraqi salt)

The same frame (Consolidation bench frame for tri-axial tests (28-T-493. 600 KG Max load)) has used for creep test to the Iraqi salt. The target of this test is to extract the elastic properties (Young modulus, and Poisson ratio).

The few quantity of raw material for the Iraqi rock salt, are forced to use one specimen for many tests. The specimen has loaded and unloaded for many steps and to the same period of times, time to change loads is less than 10 seconds, so, it has assumed to be instantaneous, in order to get Young modulus. See figure (4-63).

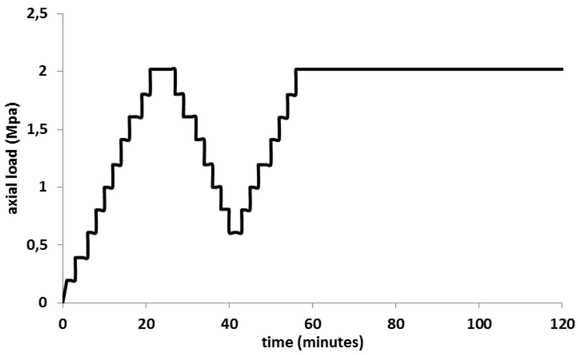


Figure 4-63 loads map for creep test of Iraqi salt.

It has extracted Young modulus for Iraqi rock salt (3.46 Gpa), as well Poisson ratio (0.34) ,See figure (4-64).

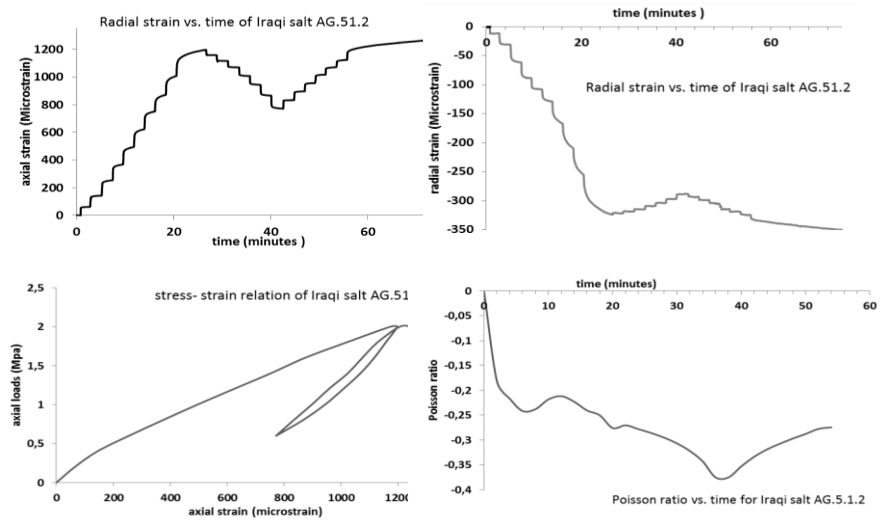


Figure 4-64 extracted Elastic properties (E,v) from creep test of Iraqi rock salt.

Fourth strain gauges (two vertical and same horizontal), two LVDT in horizontal position to recorded radial strain , as well vertical for axial strain, all of these are used to measure the deformation The Maximum load that has reached (2 MPa). Despite this small amount of loads which have applied but the rock salt generally has shown creep even for short term creep test (5 days). See figure (4-65).

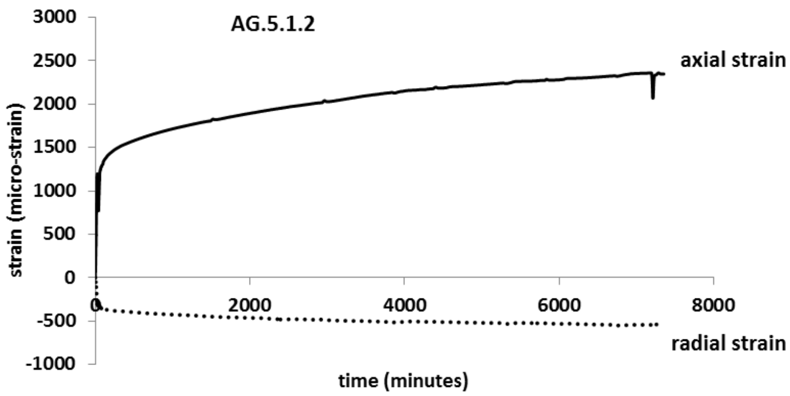


Figure 4-65 short term creep test of Iraqi rock salt

4.9.2.3 Elementary uniaxial extension test

Beside uniaxial compression long term creep test, it has tested the Italian rock salt under uniaxial extension state to evaluate behaviour of creep under this condition, but unfortunately the system has shown big anomaly(electrical noisy), even for LVDT tool, might be the reason that regarding strain gauges reading, quarter Wheatstone Bridge type have used ,that type is very sensitive for temperature, however the LVDT which has full Wheatstone bridge has shown the same anomalies, it might be fixing problem.

The Italian rock salt under tensile state has shown transient deformation till 35days, beginning with ($4.28*10^{-8}\ s^{-1}$), which was changed to steady state creep ($1,11\ *10^{-8}\ s^{-1}$), even when the load has increased after 75 days, the rock salt specimen has responsed by small transient deformation,but it has returned back quickly to steady state till the end of test. See figure(4-66).

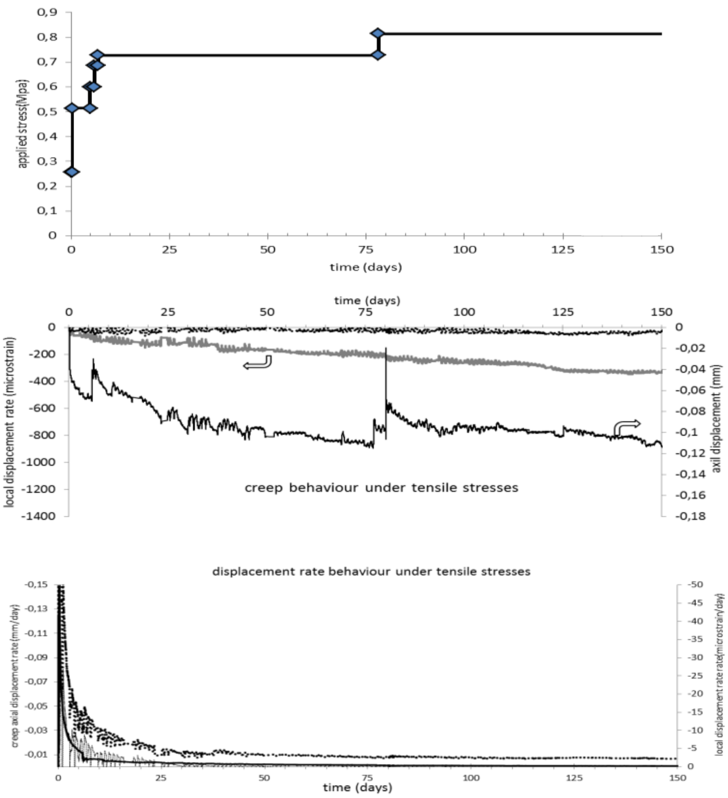


Figure 4-66 elementary uniaxial extension creep test for Italian rock salt(P1201-03), a) loads map, creep axial displacement .b) strain gauges recording (micro-stain), and .c) rate displacement (micro-strain, mm) per day.

In brief, the tensile deformation and strength of rock salt are an important consideration for the design and stability analysis of underground structures, because the rock tensile strength dictates the maximum roof span of the underground opening, the maximum internal pressure of uncased storage caverns and the borehole pressure for hydraulics fracturing.

4.9.3. Stress/ displacement controlled creep test.

Loading testing system devices are servo-controlled testing equipment's, which have the ability to apply constant loads on samples. This equipment's has the power to apply constant loads and keep it constant under accurate monitoring and recorded strains by using strain gauges or LVDT, however the critical aspect how to keep these loads for long time, especially when it will be high loads.

Part of these equipment's' can mimic in situ stresses as true tri-axial creep test, which is worked on cubic specimen by applying three independent stresses, and other part was designed to apply isotropic horizontal stresses, as well loaded the sample by different axial stresses, these apparatuses widely use. However, a Hollow cylinder apparatus cover all these apparatus because the flexibility to do any type of test.

4.9.3.1 Hydrostatic test part of tri-axial compression creep test

The Italian rock salt has been under hydrostatic test; trying to simulate the Iraqi case studies by loads and temperature, despite all limitation sometimes which has accompanied during experiments.

Different tests have done, and most of them have started by hydrostatic part in order to apply on a specimen the in situ condition as it can.

Laboratory tests of rock salt as Waste Isolation Pilot Plant (WIIP), which was designed for radioactive waste, in order to develop constitutive relations which can be used in structural design calculation and predication for long period term response of this repository and the local geological region.

Fig(4-67) has shown two hydrostatic loading curves ,the volumetric strains of specimen (7-2776) were computed as 3 times the axial strains $\epsilon 1$ while curves (7-2834.5) fits two sets of data ,($\epsilon 1$=3 $\epsilon 1$) and (ϵ=3 $\epsilon 3$), the agreement between two curves which is meaning that the rock salt was mechanically isotropic prior to testing.

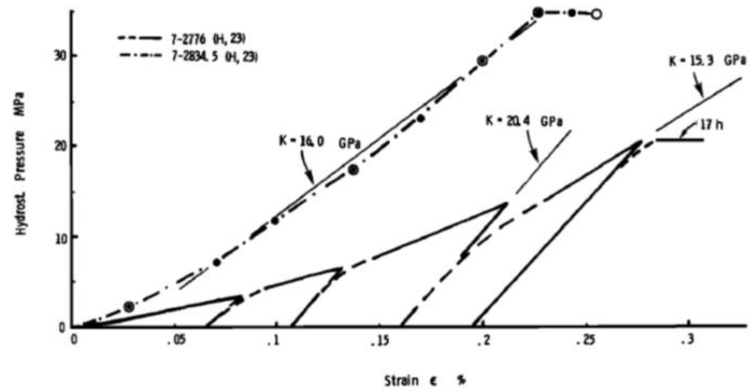


Figure 4-67 Pressure –volumetric strain curves for New Mexico rock salt subjected to hydrostatic compression at ambient temperature Open and solid circles identify data from linear measurements of $\epsilon 1$and $\epsilon 2$= $\epsilon 3$respectively (Wawersik et al 1980)

Furthermore, it can be seen the tangents for different unloading and loading parts curve of this test, and above 6,9MPa the yielded bulk moduli K in range from 15 to 25GPa, while the elastic bulk modulus below 6.9 MPa is less than this range and approximately 10GPa, the most important observation on this figure are the non-linearity between loading and un loading in low pressure before reaching to value of in situ state,

This is specialized in rock salt because the closure of micro- cracking ,pore collapsed and grain boundary consolidation ,all of these phenomena may be have happened on simultaneously, furthermore these micro- cracks remains closed during the period between unload /reload cycles.

This figure also has shown the net of consolidation, is somewhat time dependent, at 20.7 and 34.5 MPa pressure volume reductions continued for several hours. However, this behaviour cannot be seen on the Italian rock salt because the limitations of equipment. See figure (4-68), the figure has shown the bulk moduli K in range from 22 to 30 GPa.

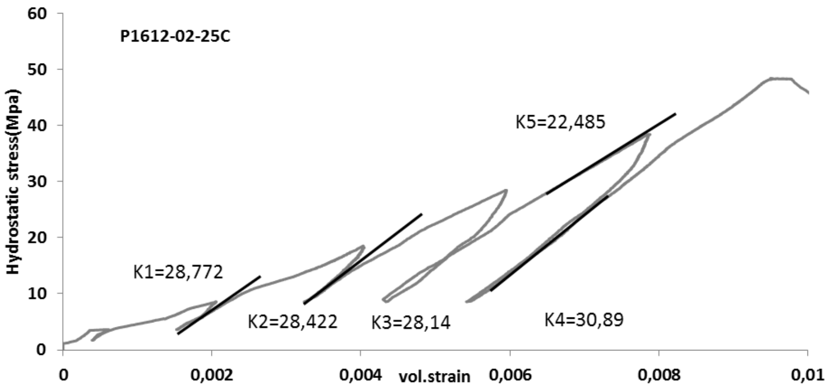


Figure 4-68 hydrostatic part from tri-axial creep test of the Italian rock salt.

4.9.3.1.1.) Hydrostatic test part and temperatures

It has investigated the effect of temperature even for hydrostatic test part of the Italian rock salt. The main observation that the rock salt has shown big strain when the temperature increasing, the strain that obtained from the 66C test, equal 10th times of the total strain in room temperature. See figure (4-69)

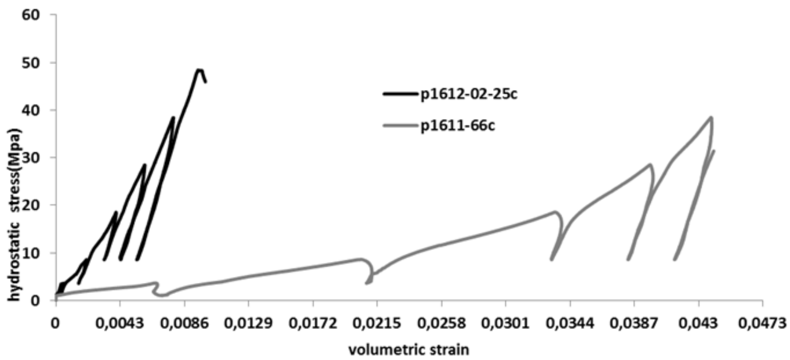


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Figure 4-69 Comparison between tow hydrostatic tests at 25C°, 66C° of the Italian rock salt.

4.9.3.2 Radially unloading tri-axial compression creep test

Here, it should be also introduced the effect of stress path on the creep, because most of triaxial creep tests, are used servo-controlled testing apparatuses. These apparatus are fixed a desire confining pressure, then applying different constant axial loads (ASTM D4406-93).The failure and creep behaviour of rock salt generally, is a function of stress state, so it directly function of the three principles stresses and stress geometry .(Hunsche et al,.1990). (Wawersik et al, .1980).

To simulate the Iraq case study, the tests have done by fixing axial loads, and then incrementally decrease the confining pressure. So, the mean stresses have decreased while the deviatoric stresses have increased, which can simulate the borehole deformation, this type of test have done under load control by using hook cell apparatus, which consist of two unites, one for confining pressure (Max 50MPa), and the other unit for axial load (Max 450MN), LVDT has used to measure axial strains as well using strain gauges (axial and radial strains).

When the mean stresses decrease, the potential of micro-cracks will activate, then the creep have happened under grain boundary sliding, on the other hand, the other creep process has activated under temperature effect inside a lattice of rock salt (glide dislocation). The first creep process is hard to be happen under traditional compression creep test because the mean stress will increase. See figure (4-70).

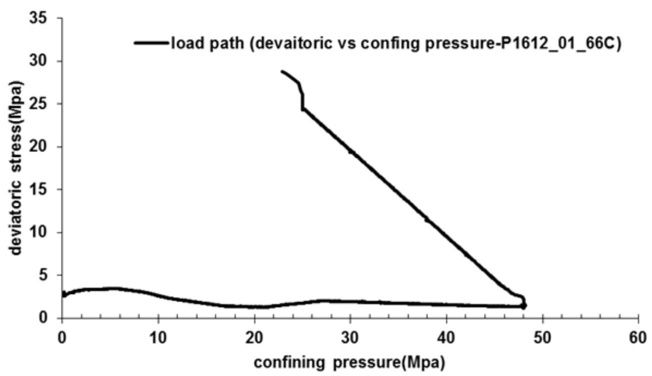


Figure 4-70 stress bath of Italian salt test hydrostatic, radially unloading creep compression test.

Furthermore, the behaviour of rock salt under conventional, radially unloading and constant mean stress creep test has been studied. The conventional creep test has shown high strain rates (Wawersik et al ,.1980).

Also, the radially unloading creep compression test has considered boundary value test problem (bench scale experiment), because through this test can re produce most engineering problems in laboratory. However, the restrictions have been faced during most of test. It has not continued put the specimen into loading step for long period of time, at least 24 hours. So, three spaces we have [(σ1- σ3), ϵ1], strain vs. time, and strain rate vs. time. See figure (4-71).

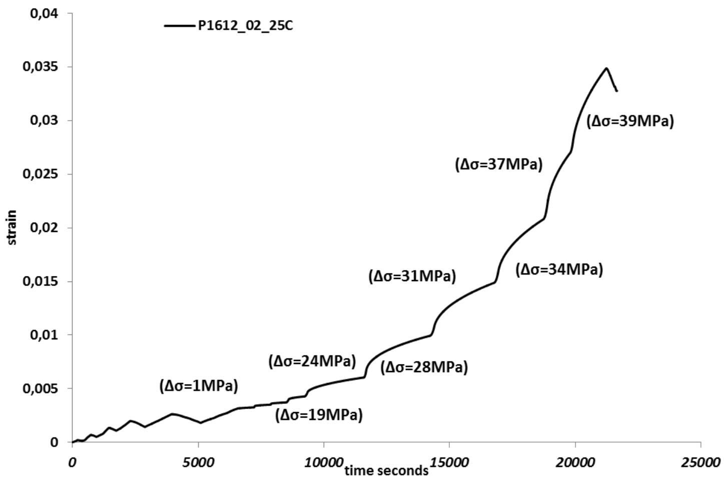


Figure 4-71 Hydrostatic test, followed by creep tests

In order to see the changes of the state of creep from transient deformation to steady state creep, then tertiary creep, it has plotted strain rate vs. time too. See figure (4-72).The figure has clearly shown at the first 6 steps, the typical behaviour of the Italian rock salt (transient deformed followed by steady state deformation) at every stage of load which has extended for (45 minutes), while the last three stages, it has shown conversion to the tertiary creep by increasing strain rate.

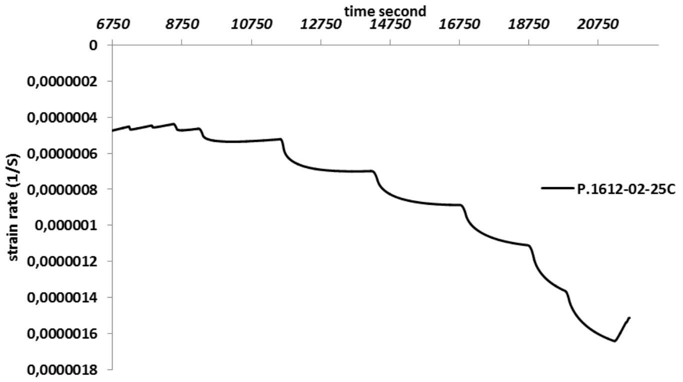


Figure 4-72 Strain rate vs time for Italian rock salt at 25C.

The last two steps has been shown transformation in strain rates from (10^{-7} 1/s) to (10^{-6} 1/s), its considerable value for creeping, which approved the deformation has passed into different processes till to enter the creep in tertiary stage. See figure (4-73).

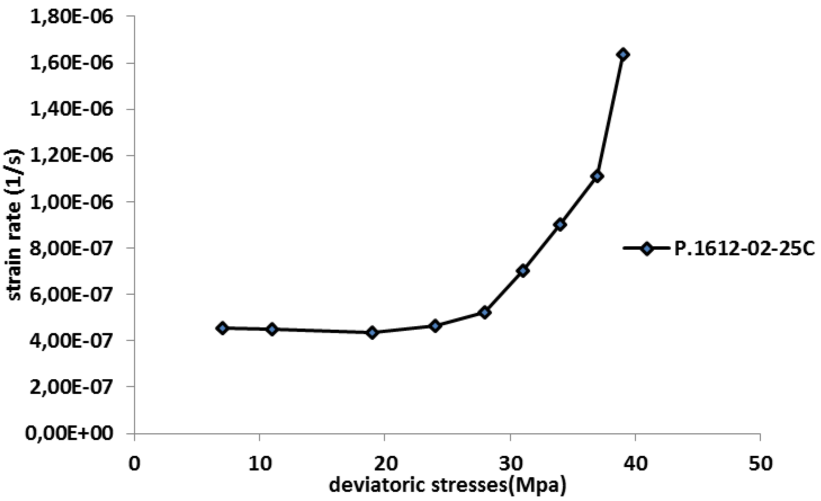


Figure 4-73 Strain rate vs. deviatoric stresses at 25C

4.9.3.2.1.) Temperature effect in radially unloading tri-axial compression creep test

Most of Iraqi case studies were happened in temperature range(60-66)C˚, so it has achieved radially unloading tri-axial compression creep test under (66) C˚.

In order to see the temperature effect, the results of the two tests (25 C˚, and 66 C˚) have been plotted for comparison. See figure (4-74)

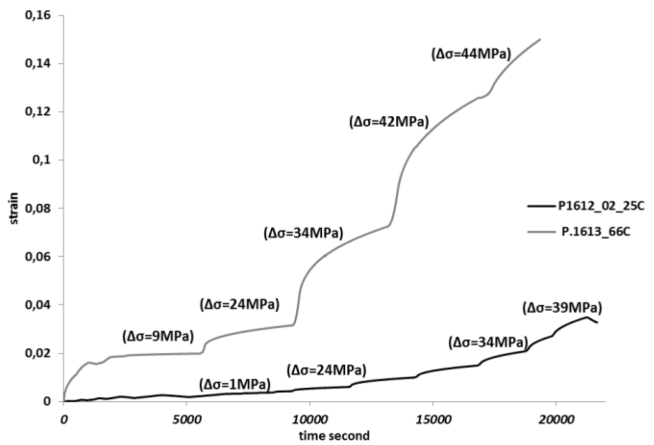


Figure 4-74 the effect of temperature on radially unloading creep tests.

It's clear the temperature effect dramatically on the rock salt specimen, for the same step of deviatoric stress (34 MPa), the amount of strain (0.072) for (66C) compare with (0.015) at (25C).

This difference has increased when the deviatoric increased too, because different creep mechanisms work under high temperature. However, at (25C) temperature, the time has not been enough to reach for steady state creep because the equipment's restrictions', as well the temperature. See figure (4-75)

The specimen has reached to tertiary creep by strain rate (1.6 x 10^{-6}) under (40 Mpa) deviatoric load at (20000) second,(25 C), while at the same deviatoric load and time, the specimen has been under steady state creep with high strain rate (1x10^{-5}).

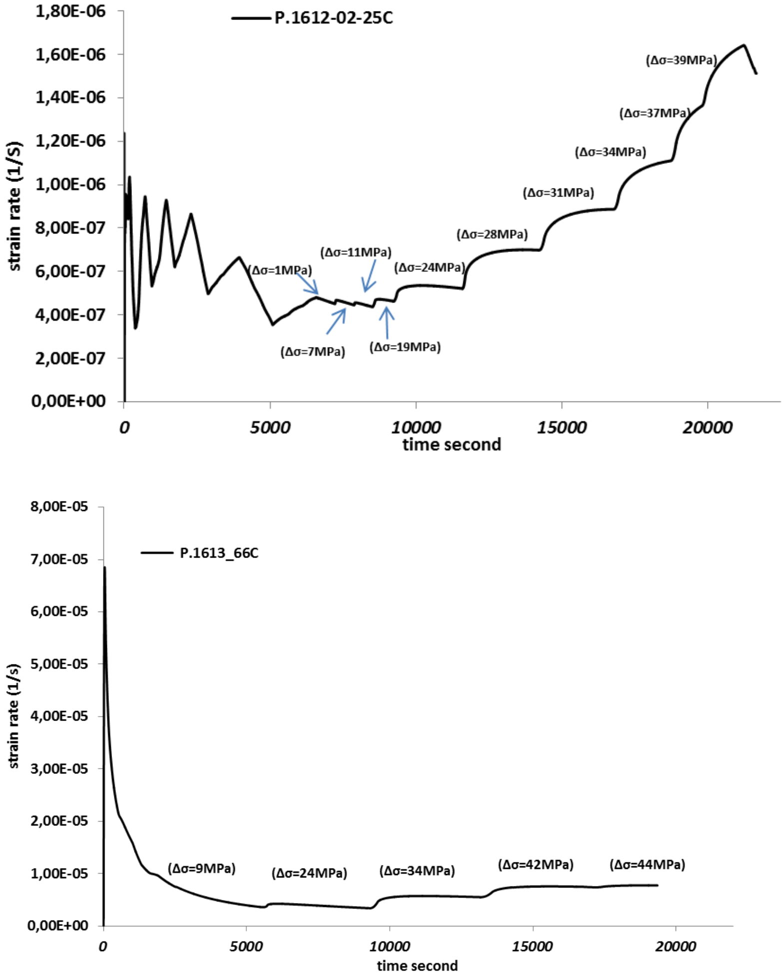


Figure 4-75 strain rate vs. time for radially unloading compression test at 25C, 66C

At the same context, it can be discovered that, both of tests have been shown same behaviour of transient deformation, but at different deviatoric steps (19 Mpa for 25C), and (24 Mpa for 66C)), but with different strain rates ($4.8X10^{-7}$ $4.6X10^{-7}$) for 25 C, (2.75 $X10^{-6}$ to 3.4 $X10^{-6}$ 1/s) for 66C.

So, the strain rate has decreased steeply when applied low deviatoric stress till to convert to steady state, then the strain rate has increased gradually at every load step of the deviatoric stress, when this deviatoric load higher the creep strength limit. This behaviour has shown in both temperatures (25C-66C) .See figure (4-76)

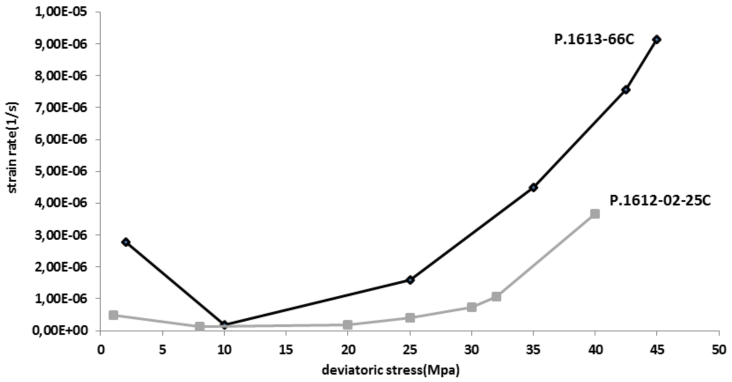


Figure 4-76 Changing strain rate (1/s) with deviatoric stress with temperature.

The final observation for the effect of temperature, the macro view for two specimens, at approximately the same deviatoric steps, the barrel shape has obtained because the temperature effect, while the other specimen has not been. See figure (4-77)

Figure 4-77 two specimens before and after creep tests with different temperatures.

4.9.3.2.2.) Processing and target of the radially unloading tri-axial compression creep test

The strain rate is very important properties in the creep test; because it can be fitted the flow law of the rock salt, then can predict the borehole closure of a rock salt. The general form is:

$\acute{\varepsilon}=A\sigma^{n}$ ……………………… (4-13)

A, is a material constant [Pa^{-n} s^{-1}], σ, is Von Mises stress [Pa], n, is a dimensionless material constant.

(A), and (n) , can be obtained by taking natural logarithm for both sides of the equation :

$\ln \acute{\varepsilon} = n\ln \sigma + \ln A$…………….(4-14).

Through this linear equation , can be fitted by plotting measured value of strain rate and Von Mises using simple linear regression which can obtained (n) , and (A) in (ln$\acute{\varepsilon}$) –(lnσ) space.

This way will lead to empirical fit that describe flow behaviour. However this method do not give any evaluation of creep mechanism, it has represented one mechanism of flow operates (steady state creep), while if it will be assumed multiple mechanisms of flow many general be active (Urai et al,.2008) (Van Keken et al,.1993).

In the same context, there are different types of micro-mechanics processing that has occurred in creep test, for two temperatures (25C, 66C), as well compare with some data from Iraqi salt, all these data was plotted on rock salt mechanics map. See figure (4-78). Despite that every mechanism has constitutive law; but can be using general empirical law for one worked mechanics.

The Italian salt and the Iraqi salt experiments data has shown, the process that controlled these experiments focus on dislocation glide, however Iraq salt has shown tending to creep even for low stress and temperature, some experimental data locate in defect less flow zone other in glide.

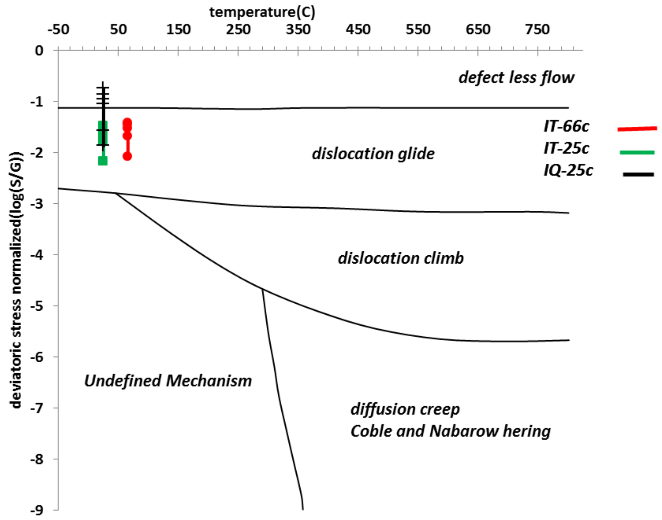


Figure 4-78 Italian and Iraqi rock salt tests results on rock salt mechanics map

Furthermore, to examine our experiment data more, it has plotted on other map which was created by collected data experiments for low temperature and wide range of rock salts which covered different laboratories (Sandia ,BGR ,Utrecht University and other laboratories)(see figure(4-79) (Urai . et al,. 2007).The solid line for room temperature solution –precipitation creep law of different grain sizes, while the broken line is extrapolating of the (grain size insensitive) dislocation creep law(n=5), it's clear both Italian and Iraqi experimental data has been taken position near to dislocation creep ,

In addition, the Iraqi rock salt has shown tending to fast creep (less than 120 days), which was happened in high differential stress (20 -30) MPa, and the same for Italian salt.

After that, it has been known, it might be the empirical flow that was designed for one mechanic process, apply in our creep tests. It has plotted the Von Mises stresses vs. strain rate to extracted the two parameters (n), and (A). See figure (4-80), and table (4-1).

Temperature (C)	Dimensionless Parameter (n)	Material parameters(A)
25	3.78	3.9491×10^{-35}
66	2.632	6.167×10^{-26}

Table 1(n), (A) parameters for Italian rock salt

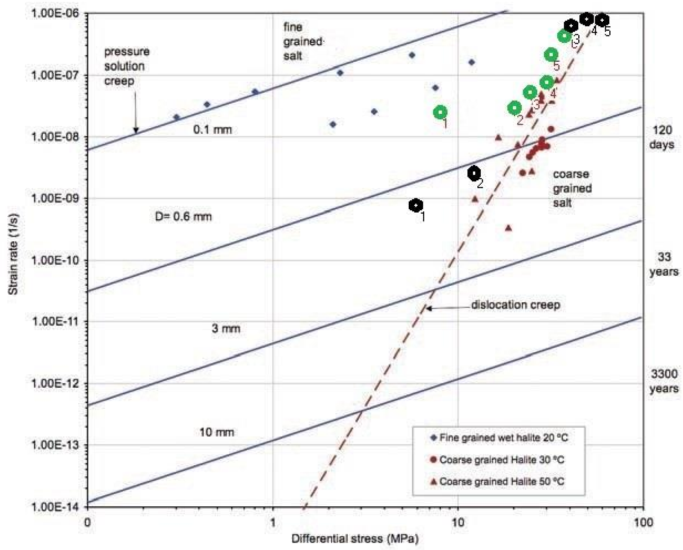


Figure 4-79 Italian and Iraqi experimental data with other worldwide collects experimental data (Urai et al,. 2007) (Iraqi salt black dot, Italian salt green dot)

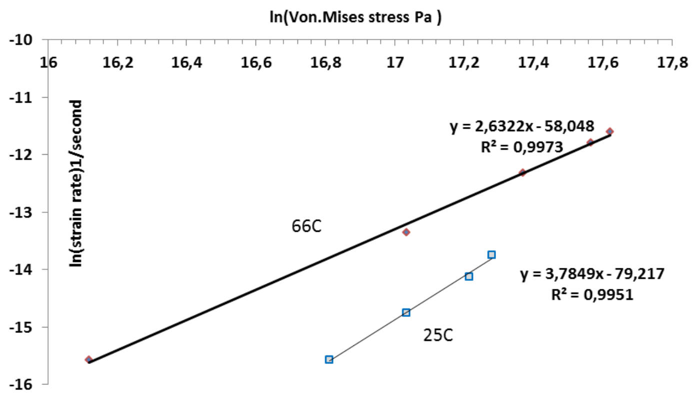


Figure 4-80 Von Mises stresses vs. Strain rate for two creep tests with different temperatures (25C, 66C).

4.9.3.3 Improvement compressive creep test

In order to overcome the restrictions for all elementary tests, some modifications have done to use GDS equipment's (GDS Lab) which support high pressure and temperatures. Due to the main part from rock salt deformation is depend on time, to reach for steady state behaviour, comparison with the test using Hoek cell apparatus.

These modifications have given the ability to support each devaitoric stresses step with respect to time.

On the other hand, even with these improvements, these laboratory equipment's do not support long term creep (more than several months), so it can be classified as short term creep test.

The short term test is important test especially for borehole of oil well, which can simulate mechanical behaviour to rock salt during drilling borehole, Actually, some part of borehole for oil well are exposed to variance devaitoric stresses for short term period; then the rock salt is responded on different patterns of deformations (transient creep, or steady state creep or may be tertiary creep) depending on the stress rates.

On the other hand, for repositories which reserve radioactive material, the short time creep test can show just the behaviour of rock salt after excavation processes, while the long term test (more than one year) will be suitable for this type of structural engineering.

So, one test has done on the Italian rock salt, and it has applied temperature effect in order to see behaviour of this rock during period relatively longer than the previous tests, it has used GDS lab equipment that gives more tolerance to do the test in period reach to weeks or may be more.

4.9.3.3.1.) Results and analysis

The figure (4-81) has summarized the creep test , this figure has divided for different sections due to deviatoric stresses (different confining pressures) and temperature, most sections of test has done at room temperature (21 C), while the other parts at (60 C). These sections of tests have separated by hydrostatic periods to let the specimen entering into healing process (by applying 30 Mpa axially and radially).

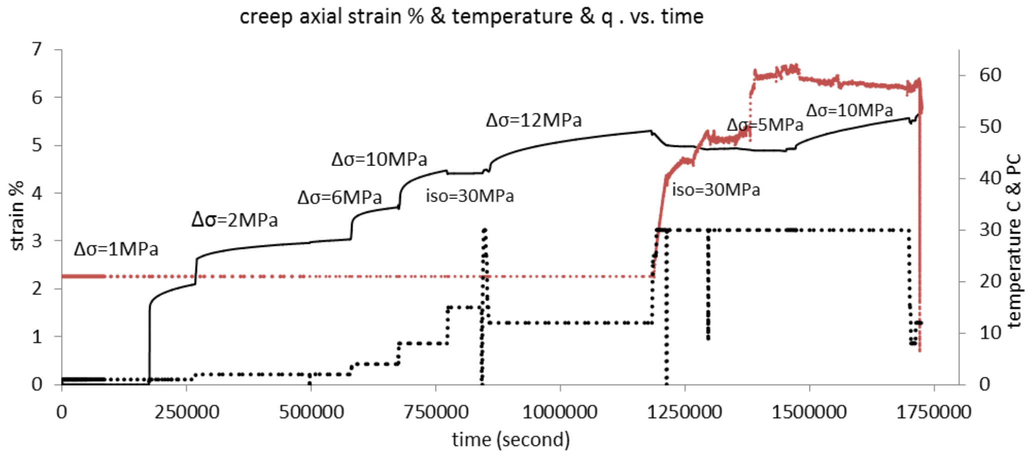


Figure 4-81 short term creep test under different condition (temperature, stresses) for Italian rock salt (P-1614)

This healing processing was used between different parts of the test, is important to evaluate the rock salt correctly.

So, the first deviatoric load (1Mpa), with confining pressure (1Mpa), the first response, strain (1.8%),the rock salt has been shown transient creep rate starting ($9.24*10^{-8}$ s^{-1}), then the strain rate has decreased ($8.00*10^{-8}$ s^{-1}) till the next load (2Mpa), but with increase confining pressure too (2Mpa), it has got small changing in strain. The confining pressure will be more effective in range (1-3) Mpa, for fixed deviatoric stress. See figure (4-82). However, when it will be high the rock salt is being under non dilatant situation, and then getting steady state creep.

The Italian rock salt has shown transient deformation under this low deviatroic and it did not show steady state while, (more hardening rather than recovery), however, in the elementary uniaxial creep test, the steady state creep was reached after (3days) at maximum load (5 Mpa),the loads rate stand behind that.

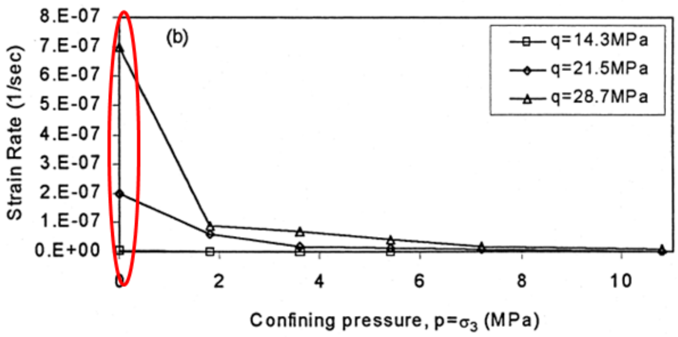


Figure 4-82 effect confining pressure on creep test of rock salt.

Many of published papers (Peach et al, 2007) (Leite et al, 1998) have shown effect of confining pressure (below 3MPa) on transient deformation. Some sections of the test has covered this point so, it can be said that the Italian rock salt has shared other rock salts to the same behaviour when the confining pressure increase ,the rate of deformation try to be steady state,. See figure (4-83).

The figure has shown, that just the first increasing confining pressure (1-3) Mpa, the rate of deformation has decreased, while after (3Mpa), the strain rate is stable, till the end stage of (12 Mpa), after this value, the rate of deformation has not been too big.

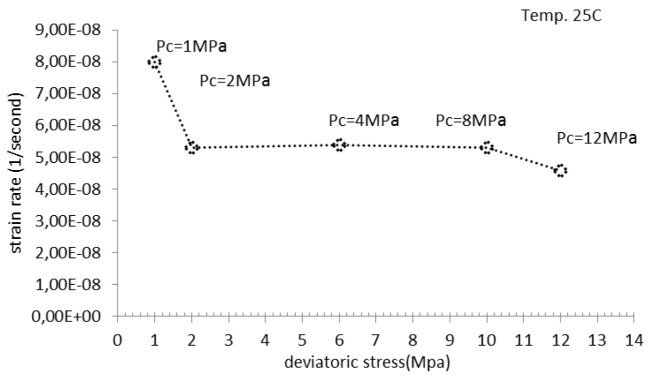


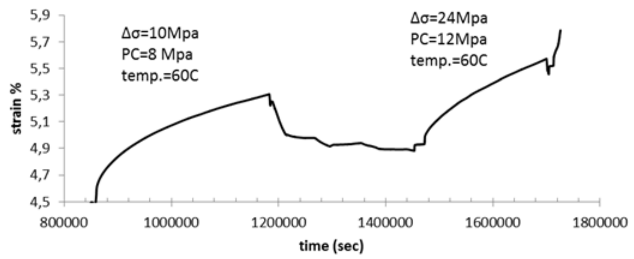
Figure 4-83 strain rate vs. deviatoric stresses for different confining pressures.

Furthermore, the Italian rock salt during this test has shown transient deformation which has extended more than (10) days.

On the other hand, the same rock for the first periods of elementary uniaxial creep test (Cantilever apparatus), the transient deformation has extended (2) days, and then entered in steady state deformation. However, the rock salt through this test has approximately reached to steady state after (17) days, under effect of temperature and confining pressure, with respect it has loaded with many steps, and the time has not been enough between some steps to see exactly the changing from transient creep to steady state.

Generally, the steady state creep has clearly appeared when the temperature reached to (66C), at the last period from the test, which consist of many steps too.

However, the rock salt has responded to devaitoric step by changing from steady state to the transient deformation, then return back to steady state. See figure (4-84).



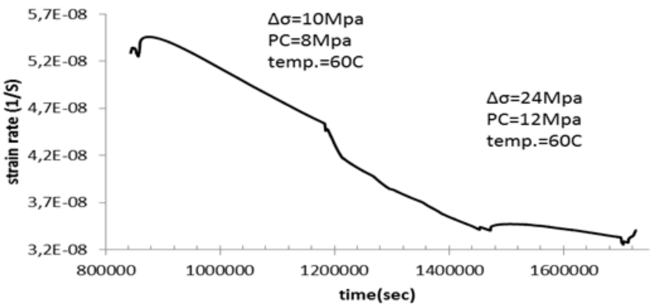


Figure 4-84 , showing transient deformation rate after reaching steady state

The third section which connected to this test, has discovered the temperature effect on creep behaviour of the Italian rock salt, the equipment and rock salt have heated by using temperatures belts till (60C). The specimen has tested by two loading stages, (5MPa) for more than (1 hour), (10MPa) for more than (2 days) while confining pressure has kept constant at (30MPa).

The other two periods (one hour for each), 1st deviatoric stress (10 Mpa) with confining pressure (8 MPa), 2nd deviator stress (12 MPa) with confining pressure (12 MPa) to evaluate the effect of temperature on those loads. See figure (4-85).

It's clear the effect of temperature, the strain rate has responded to the change (temperature, devaitoric stress, confining pressure), but actually these changing are not noticeable because most of them has ranged in (10-8). Despite the increasing the deviatoric stress with fixed confining pressure (30Mpa), the strain rate has been stable in one value ($3.5*10^{-8}s^{-1}$).

On the other hand, at fixed deviatroic stress (10Mpa), and fixed confining pressure (8Mpa), the temperature has changed (25C to 60C), the strain rate has affected by decreasing from ($5.8*10^{-8}$ s^{-1}) to ($4.5*10^{-8}$ s^{-1}), while at the same temperature (60C), increasing the confining pressure (8Mpa to 30 Mpa) has led to decrease the strain rate ($4.5*10^{-8}$ s^{-1}) to ($3.8*10^{-8}$ s^{-1}).

Furthermore increasing deviatoric stress will be more effect than confining pressure under temperature effect, because it has gotten strain rate ($3.2*10^{-8}s^{-1}$) for deviatoric stress (12Mpa) and confining (12 Mpa), which is the same strain rate under (30 Mpa) confining pressure but (10Mpa).

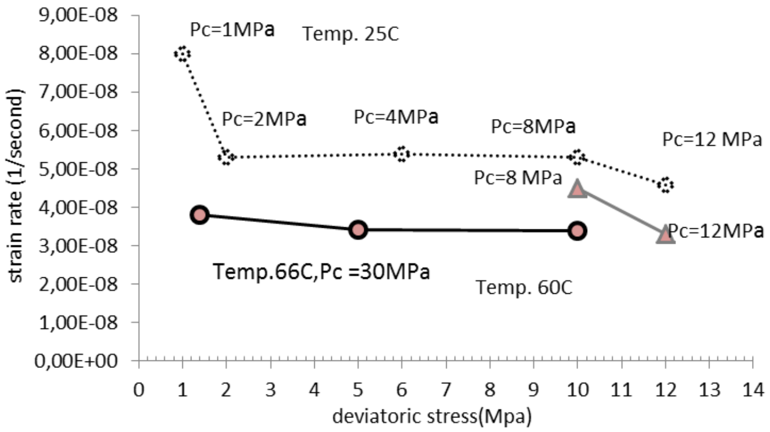


Figure 4-85 strain rate vs. deviatoric stress with constant confining pressure (30MPa), and 60C temperature.

As well, the recovery process is dominated at low temperature, due to stress-assisted thermal vibration which allows dislocations to cross a obstacles, or might be healing process has supported the specimen during the test, that support the steady state creep to be continued.

Generally, to summarized all steps that have done on the specimen P.1614 the figure (4-86) has shown the strain rate changing during this test, as it can see, despite all steps of deviatoris stresses, which have included hydrostatic periods. The transient period has extended for approximately 17.5 days, while the multistage test for the Italian rock salt P.1613-66C, the period for each stages have extended for one hour or less, but the transient creep has finished at (2 hours), the temperature and loading rate stand behind that.The specimen P.1614 has been under low deviatoric stresses but with high confining stresses (30 MPa) for not short period of time (3 days), the creep strain has drawn down, it can say the rock salt in healing process, furthermore, the specimen has not shown any macro-cracks. So, it has thought, if there is microcracking which has happened during the history of the test, it would be healed. In brief, generally, at temperature (0-200) C, and when the deviatoric stress do not cross dilatancy boundary, the deformation is caused by dislocation creep

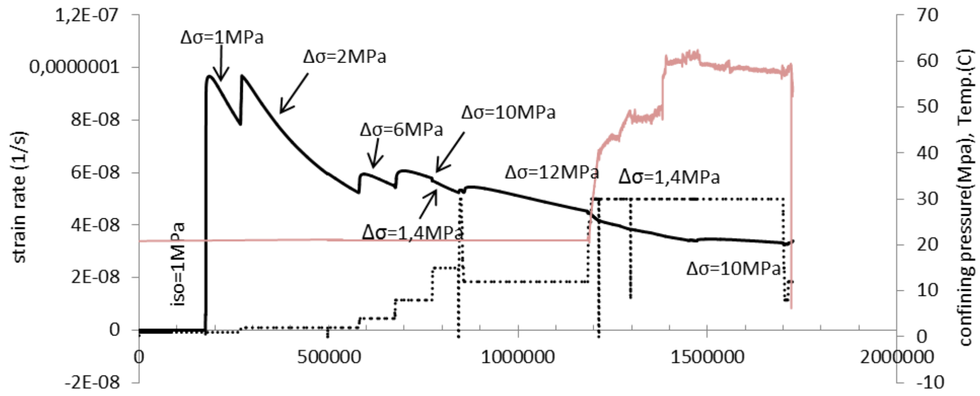


Figure 4-86 strain rate vs. time for Italian rock salt (P-1614) of different conditions from temperature and stresses.

4.9.3.4 Advanced creep test.

After the results which have extracted from elementary creep tests, thinking to improve the experiments by using wide range of stresses ,and more options to explore a mechanical properties of rock salt under different circumstances as confining pressure and temperature for appropriate time. The hollow cylinder test could be possible using triaxial apparatus, because it can use hook cell with temperature but to short period time (not to more 8th hours), that will not be suitable for hollow cylinder test (boundary value problem experiment).

So, modification and improvements to overcome the restrictions have been done, by add some accessories to (GDS Lab) equipment's', then can be using hollow cylinder specimen, accompanied with effect of temperature during the test.

4.9.3.4.1.) Steps of modification

Strain gauges: Cables passage

The key point for this modification is to create a passage for cables then, getting data from strain gauges. This passage gives ability to connect between two different regions of temperature and pressure, a small plug has created to insert into a hole inside pressure cell.

This plug is able to accept passing four cables under working pressure of the triaxial cell without any leakage. So, it can transfer all data from strain gauges (vertical and radial), which have already pasted on the specimen. Different types designed of these plugs have tested, in order to choose the best one for the task.

The best design is stainless steel solid plug with four ports to pass cables, and sealed by proper sealing material (liquid gasket) and (silicone compounds), however, it has tried to use sealed rubber material with suitable seats(both of them have four ports) but the results has not encouraged. So, it has reached for final design, which consists of conical passages to accept the numbers of cables, and has filled in different types of resin, two compounds resin (BSF Araldite A, B).

Pressure test vessel (quick test)

The other important step that has done, It has manufactured small vessel (140 x148 mm), that give ability to do a quick test, by quick assembled and disassembled in order to reduce consuming time. It consist of a cylindrical room (401.9 cm3), equipped with two ports to accept the plugs. See figure (4-87). This vessel has designed also to do hydrostatic test for small specimen, and to test the plugs that will use in the triaxial cell.

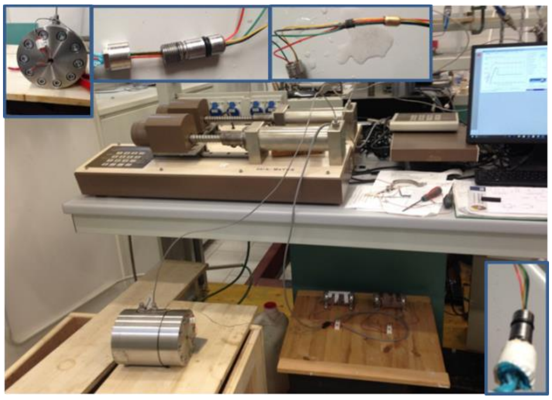


Figure 4-87 Pressure test vessel with plugs which have ability to pass cables under pressure

Strain gauge test

Many tests have done for all plugs and cables, under temperature and pressure, some tests for rock salt, other to Plexiglas disk, after pasted strain gauges, and reaching with pressure till (30 MPa), and temperature till (62 C), see figure (4-88) in order to choose which the best fit way.
So, results have shown the ability to use strain gauges in variety circumstances even with high pressure, and temperature to long period time.

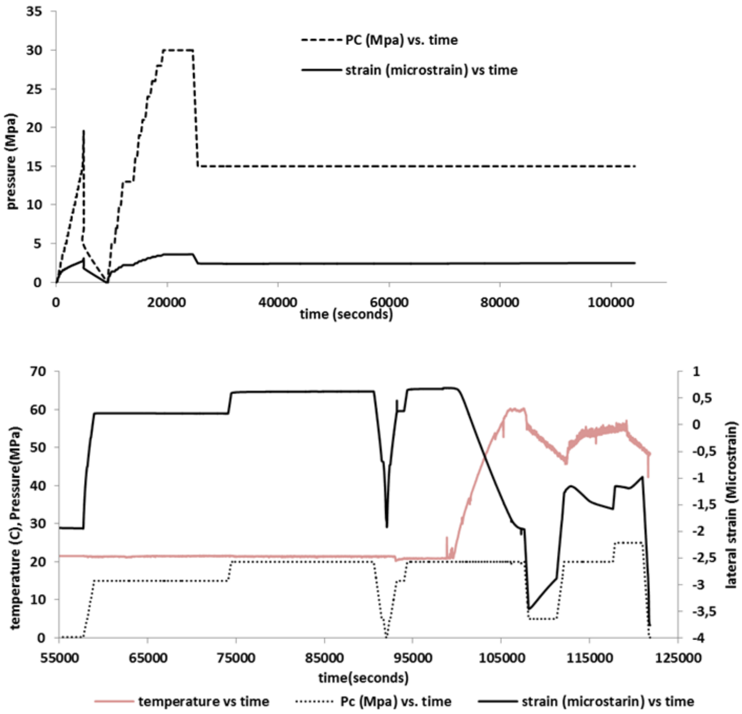


Figure 4-88 pressure test of strain gauges under 30MPa for more than 28 hours at room temperature for Plexiglas disk(top), pressure test for strain gauges, and all sealing plugs with and without temperature, as well pressure (bottom).

4.9.3.4.2.) Results of advanced creep test for Italian rock salt.

So, after lot of tests those have covered different type's adhesive materials, and cables, to get best results. The advanced creep test of the Italian rock salt (P1615) has been done.It has been simulated the in-situ boundary conditions (Iraqi rock salt case studies), in order to compare the behaviour of those two salt rocks.The test has done by applying hydrostatic pressure (10 MPa) for (15 hours), and then it has increased to (30 MPa) for (1.5 hours), then the creep test has done under confining pressure (30Mpa), by applying the 1st deviatoric stress (30) for (5th hours), then the 2nd deviatroic load (40 MPa) for more than (15th hours), finally apply deviatoric stress (50 MPa), see figure (4-89)

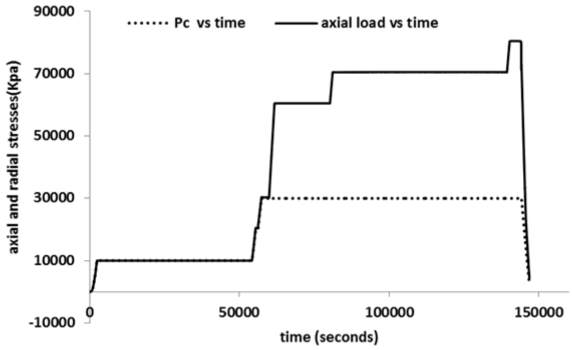


Figure 4-89 load distribution for advanced creep test of the Italian rock salt (P. 1615).

The behaviour of the Italian rock salt and the Iraqi rock salt has been approximately the same, however, the Italian rock salt has failed under ($\Delta\sigma$ = 50 Mpa) while, the Iraqi rock salt has not shown any failed even the load was ($\Delta\sigma$ =60 Mpa). The reason behind that, it might be differences in mineralogy because, Iraqi salt has grain more than (50mm) while the Italian rock salt (3mm), despite both rock salt are secondary type and same age (Miocene) but under different geological environments, then the test has given important information for the step of the hollow cylinder . See figure (4-90).

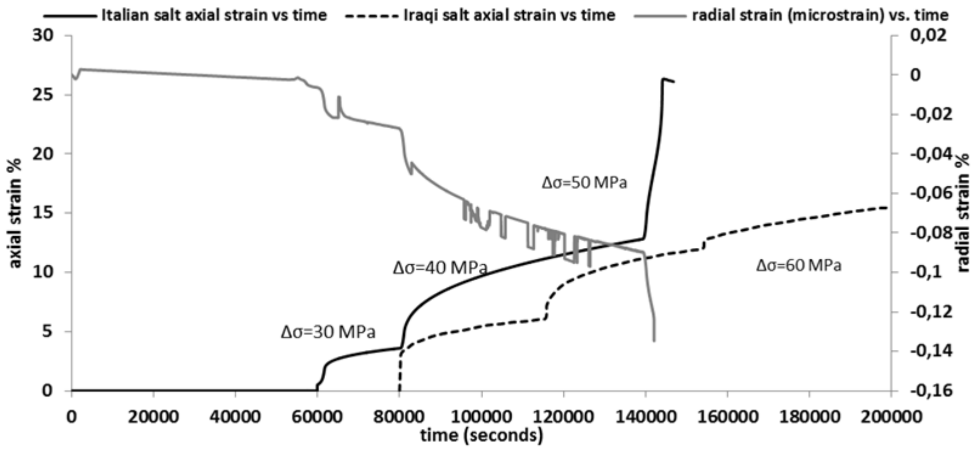


Figure 4-90 Creep test for both Iraqi and Italian rock salt under (30MPa) confining pressure under room temperature

The other interesting point through this test is the success to use strain gauges with the new accessories in the triaxial cell apparatus.

Despite, one strain gauge (lateral one) has worked, while the other have stopped recording since starting the test because, they have destroyed during installation of the triaxial cell. It has been noticed some difference in the strain rate behaviour between Iraqi and Italian rock salt , when converting from transient to steady state at every load step. See figure (4-91).

The figure has shown this difference, that the Italian rock salt has responded for every load by changing from steady state to transient deformation clearly then returns back after period of time extending (3-5) hours, however, this behaviour has not clearly recognized for the Iraqi rock salt. It might be the grain size difference between the two salt rocks. However, the ISRM (Brown et al ,1981) recommendations on the specimen diameter with respect to maximum grain has not always fulfilled.

In addition, the care about the sample selection help to reduce the effect of an inhomogeneity and grain size, because the grain size effecting on the crack coalescence stress but not the crack initiation threshold. (Eberhardt el at, 1998).So, the variety of rock salt was caused by: geological structure (bedded salt, dome salt), genesis (primary salt, secondary salt) and texture (gran size, impurities) (Ghoreychi et al,. 2012)

The strain hardening and recovery processing are governed by dislocation processing, which works inside the lattice, especially when the grain have been contained more defect lattice , when both processing are in balance ,the steady state will get , while this balance are not obtained ,the creep behaviour changes to transient deformation or may be tertiary deformation.

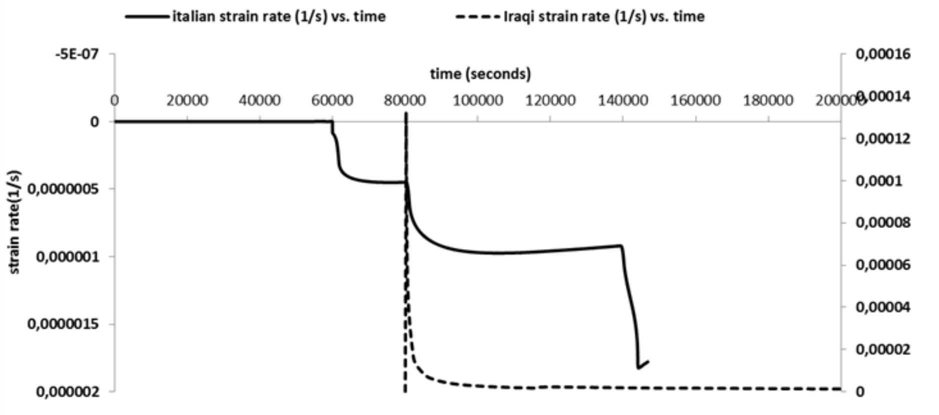


Figure 4-91 comparison between the Italian rock salt and the Iraqi rock salt by strain rate vs. time.

Different methods which are used to detect initiation of micro-cracking in rock salt, which is called damage criterion that are differ to failure criterion: acoustic velocities, acoustic emissions, and volume change since, viscoplastic behaviour of rock salt is not accompanied by any volume change, so the triaxial creep test has used to show this behaviour (compaction, incompressible, and increasing volume till the failure). See figure (4-92) (Düsterloh et al,. 2012)

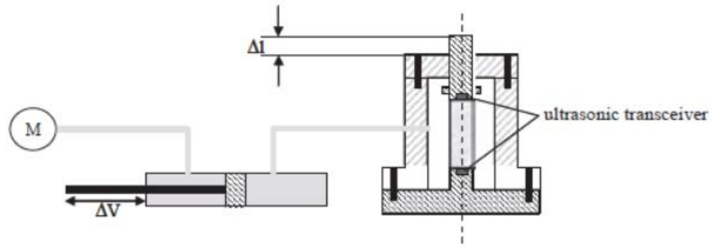


Figure 4-92 Schematic diagram of the dilatancy measurement apparatus (Düsterloh et al,. 2012)

So, it can be estimated the dilatancy boundary from the volumetric change of the pumped oil, which reflects the change volume of a specimen. See figure (4-93).

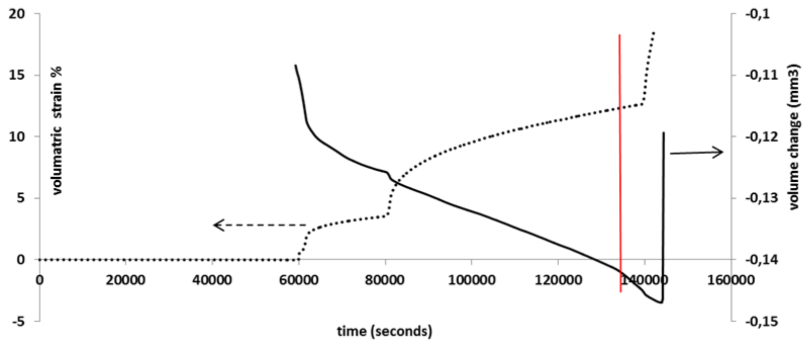


Figure 4-93 volume change and volumetric strain vs time for the Italian rock salt (P.1615).

The figure has shown decreasing volume of specimen, which meaning compaction state, till approximately to the end of the 2nd loading step at time (38,8 hours) ,changing the compression to expansion, however it has not been clear this changing in volumetric strain trend. This point show the strength of dilatancy is (40 MPa) under 30 Mpa confining pressure.

The same behaviour has been shown by looking for percentage volume change of the specimen vs axial strain relation, which indicated for C/D boundary, the stage of initiating micro-cracking on the rock salt. See figure (4.94).

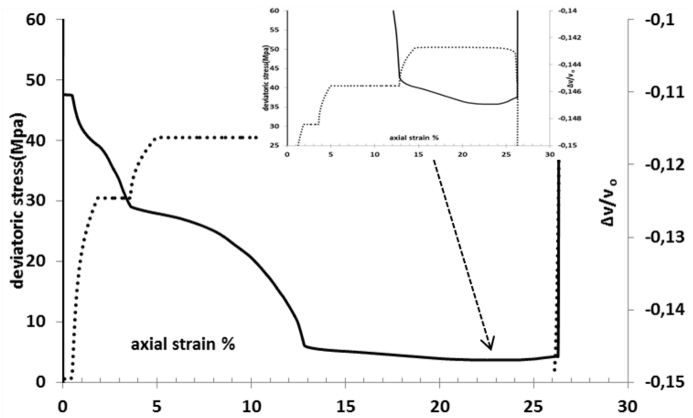


Figure 4-94 percentage volume change, and axial strain vs. deviatoric stress for the Italian rock salt .P1615.

Finally, the macro view of the specimen after the test, has shown ductile deformation.See figure (4-95)

Figure 4-95 Italian and Iraqi salt after advanced creep test

Results advanced creep test for Iraqi rock salt.

In order to get good view for Iraqi salt, and to be close of the boundary condition to get this creep behaviour, it has been selected (30MPa) as confining pressure. The matrix of the tests as follow:

- Creep test under confining pressure (30Mpa), with three stages of deviatoric stresses steps (40, 50, and 60 Mpa) under room temperature.
- Creep tests under same confining pressure (30Mpa) with also three deviatoric stresses steps (40, 50, and 60 Mpa) but under (55) C.

So, the target is to simulate the effect of temperature on behaviour of Iraqi rock salt, because it's important step to predict to the loads on the casing pipes .See figure (4-96).

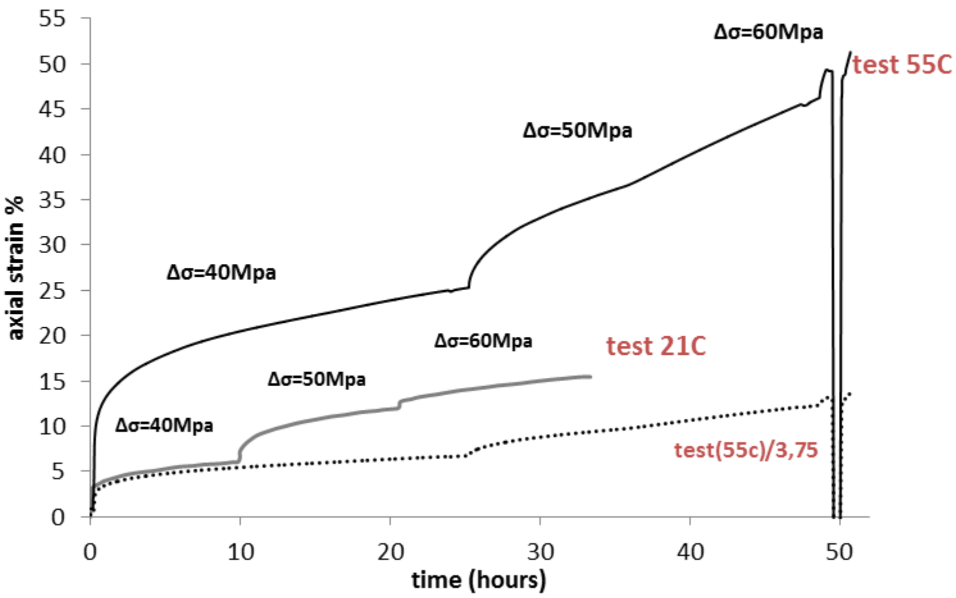


Figure 4-96 Two advanced creep tests for Iraq salt for two different temperatures.

The general view for these two tests, are the temperature effecting for Iraqi salt. For temperature near to (60) C, the creep deformation has increased (3.75) times for room temperature, while the long period of time has not increased the creep deformation too much because, it has already been in steady state condition. The creep test at (21) C, the Iraqi rock salt has shown transient creep deformation till approximately the end of the test (after 30 hours), the strain rate decrease from ($1.4*10^{-4}$ S^{-1}) till the steady state ($7.876*10^{-5}$ S^{-1}), despite the deviatoric stress has been changed (40 Mpa to 60Mpa).

On the other hand, the Iraqi rock salt has responded to the creep test at (55)C, by high deformation rate started from ($5.2633*10^{-3}$ s^{-1}) as transient creep rate during apply isotropic part to reach to the required confining pressure (30Mpa), however the difference between axial and confining stresses has (0.5 Mpa), and during this part , the strain rate has sharply decreased trying to reach steady state at rate ($3.515*10^{-7}$ s^{-1}) near to the first step of deviatoric stress . Again, the rock salt has shown another transient deformation because increasing the dislocation density which is represented by hardening, so through (0.5Mpa) deviatoric stress and just after (20 hours), the temperature has been effected to change the behaviour from transient to steady state, even the load was so small. Therefore, the first high devaitoric stress (40 MPa) has not been effect to much to change the state of creep from transient to steady, ($2.068*10^{-6}$ s^{-1}) ($1.65*10^{-6}$ s^{-1}), so this changing is not big, it can be said, the rock salt has been entered in steady state during the period of isotropic test (use deviator 0.5Mpa from technical point of view). The temperature plays big role to increase the dislocation density, then increases the impeding to this dislocation which responsible for softening till to reach for balance quickly. See figure (4-97).

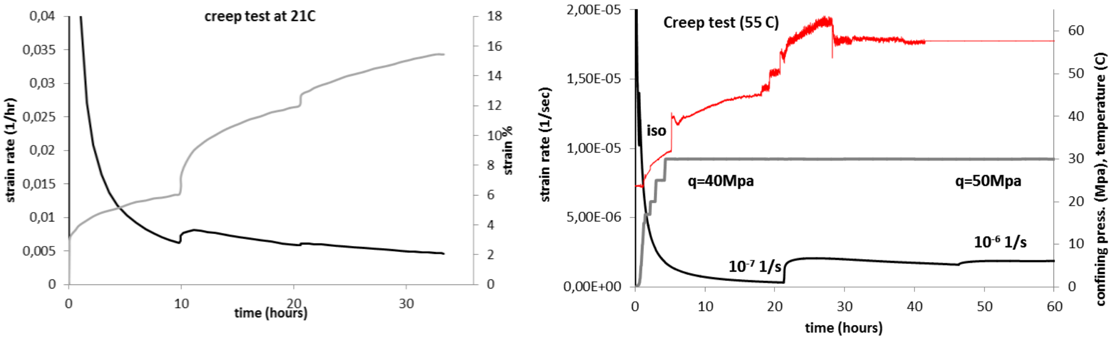


Figure 4-97 strain rate for two creep tests of different temperatures.

it has been achieved two cycles of loading-unloading to study the behaviour of stiffness during two deviatoric stress steps (40Mpa), and (50Mpa), it has found that the stiffness have increased from (28.4Gpa) to (35 Gpa). See figure (4-98).

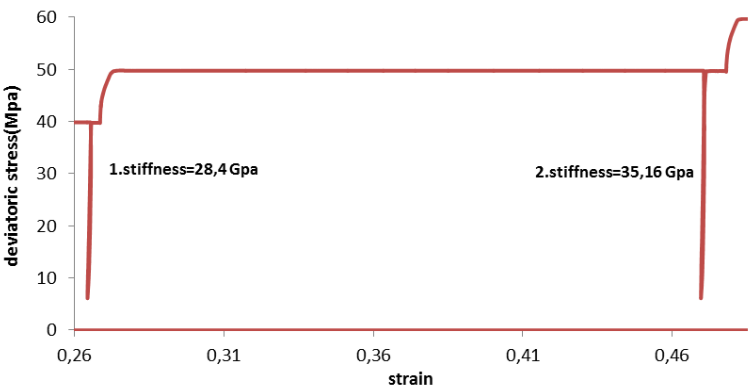


Figure 4-98 two cyclic unloading-loading through creep test.

Furthermore, temperature accompained with stress from (21) C to (55) C has accelarated to the Iraqi rock salt to cross the dilatancy boundary during second loading step (50Mpa), then accumulated all microcracking till the beginning of the third loading step (60Mpa), which clearly the rock salt has entered to the tertiary creep .

One the other hand,the Iraqi rock salt has not reached to the tertiary creep at the same stress path but at room temperature. See figure (4-99)

Figure 4-99 rock salt specimen before and after creep test (55C).

To complete the picture for the creep , it should be compared between Italian rock salt with Iraqi rock salt, which have share the same geological age (Miocene) but different by excavation depths. Here it has been superimposed the two creep tests at room temperature (21C). See figure (4-100), (4-101).

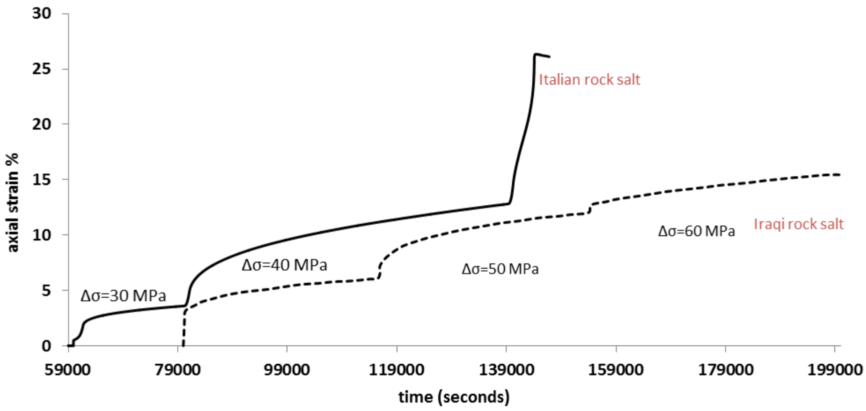


Figure 4-100 compare between Italian and Iraqi rock salt during creep test (21) C

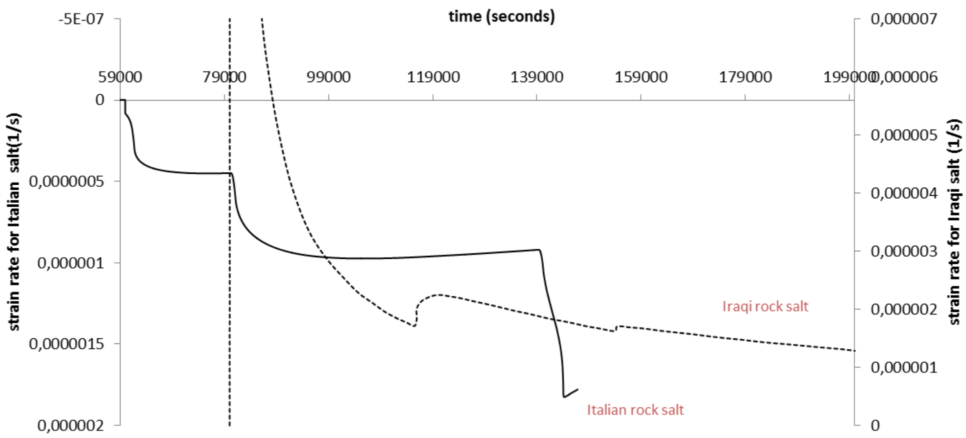


Figure 4-101 , strain rate comparison between Italian and Iraqi rock salt during creep test (21) C

Its seem the Italian rock salt is weaker than Iraqi salt from creep point of view, the Italian rock salt has reached to tertiary creep at deviatoric load (50 Mpa), and then failure.

The Italian rock salt at the first load (30Mpa) , the rock has been reached to steady state rate ($4.48*10^{-7}$ s-1) that agreed with the steady state strength of creeping, meaning stable trend , however this trend has not found for (40Mpa),because its reached to steady state rate ($9.73*^{10-7}$s-1) for a while , then increased to ($9.22*10^{-7}$ s-1), because this deviatoric stress is more than the steady state creep strength . See figure (4-102).

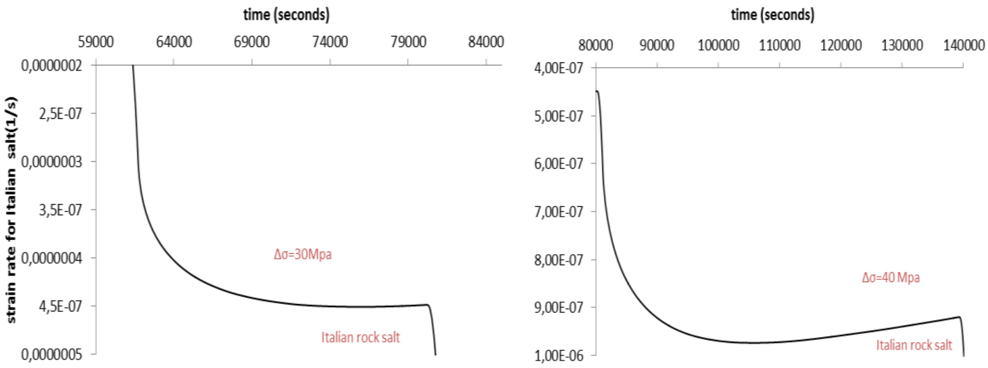


Figure 4-102 comparison for steady state creep of two steps Italian rock salt

On the other hand, seemingly the first stage of load (40Mpa) to the Iraqi salt has initiated strain rate starting ($1.4*10^{-4}$ S-1), then decreased sharply but the time has not been enough to reach steady state rate ($7.876*10^{-5}$ S-1).

The rock salt has responded to load stage (50Mpa) by changing strain rate($2.2*10^{-6}$ s-1), then return back near to the steady rate ($1.62*10^{-6}$ s-1), because last load stage (60Mpa), the changing in strain rate has not been big ($1.29*10^{-6}$ s-1), however, the last trend of the Iraqi rock salt has reached for steady state creep strength. See figure (4-103)

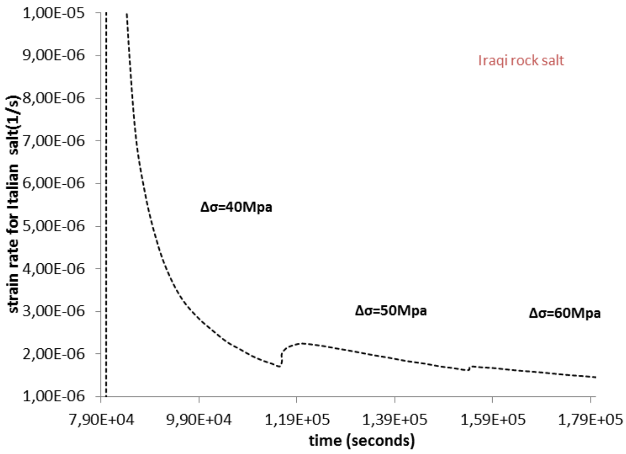


Figure 4-103 changing strain rate with loads for Iraqi rock salt

In brief, the Italian rock salt has reached quickly to steady state creeping after two steps, while the Iraqi salt after three steps has entered in steady state despite the load is too much compared with Italian rock salt. The micro-structure (grain size) and impurities are clearly effect for two types of the rocks , because Iraqi salt has big grain size (more than 50mm) ,compare with (3.3mm) to Italian rock salt, furthermore, the impurities into the Iraqi rock salt are more than Italian rock salt.

Chapter 5: Design advanced hollow cylinder apparatus for borehole stability

5.1. introduction

The great majority of studies on rock salt are conducted through laboratory tests (Leite et al ,.1998) (Düsterloh et al, 2012) (Mahmoudi et al ,. 2016). Main Parts of them connect to the standard tests (Uniaxial, tri-axial...); a few to the hollow cylinder test (thick or thin wall), depending on the research demands.

Due to the investigation of elastic, inelastic deformation, fracture, failure , and simulation the behaviours for wide variety of stress paths, which gives the hollow cylinder test the importance.

"In the context of nuclear waste disposal in clay formations, laboratory experiments were performed to study at reduced scale the excavation damaged zone (EDZ) induced by the construction of galleries in the Boom clay formation. For this purpose, thick-walled hollow cylindrical samples were subjected (after recovery of in situ stress conditions) to a decrease in the inner confining pressure aiming at mimicking a gallery excavation". (Labiouse et al,.2014). This example, was shown, the deformation around central borehole depend on the orientation of specimen with respect to a bedding plan.

Other example that using (thick wall hollow cylinder) specimen to study the behaviour of a weakly consolidated formation that consist of sand poorly cementing agents bonded (clay, calcite). This type of formation might be faced during a several mineral exploration drilling sites in Australia (Hashemi et al,.2015).

The effects of differrent parameters such as water and cement contents, grain size distribution on the deformation inside borehole, was studied. However, most of articles that was published, has been investigating other types of rocks as (sandstone, limestone...) (Hoskins. et al,. 1969) (Ewy. et al,. 1990) (Papamichos. et al,.2010) (Santarelli.et al,.1986) (Papamichos. et al,.2010) (Abdulhadi et al,.2010) (Lee. et al,.1999) (M.Hosseini et al 2000) (Blümling et al ,.2007) rather than rock salt (Senseny. et al,.1989)(Morgan. et al,.1991) (Rahimi et al,.2015)

Most of difficulties of the thick wall hollow cylinder test connect with testing facilities and developing such facilities, some published researches have been shown these developments (Monfared et al,.2011) (Valdueza Lozano et al,.2003) (Lee et al 2002) (Bons et al,. 1996) (Hashemi et al,.2015) (O’Kelly et al,.2003) (Alsayed et al,.2002) (Haimson et al,.2003).

The experiments have been considered the success key for any research because it can be studied the effect of contributing variables in the problem, as well it can validate any model (numerical, analytical).

So, this chapter has focused about, how can be used triaxial apparatus by developing some parts or by modification other, to design then create apparatus to accept hollow cylinder specimen inside pressure vessel. The developments have introduced the solutions for the challenges.

These challenges can be summarized:

Firstly the sensitivity of rock salt in general, for most experimental processing, starts from extracting core specimen till to do the experiments.

Secondly, the capacity of the equipment’s which should cover the deformation of rock salt during not short periods for range of temperatures and pressures, depending on boundary conditions to engineering structural.

Thirdly those connect with measurement tools which should be used into hard environments. The engineering structural condition should be simulated, which need to know deformations. These deformations require using measurement tools under high pressure and temperatures to different environments as humidity.
So, the plan has put to simulate the case study, that needs to use hollow cylinder specimen, then draw outline its difficulties.

5.2. Practical steps to create hollow cylinder apparatus for studying borehole closure

5.2.1. Specimen preparation

The preparation rock salt specimen for the experiment is important step because sometimes has been considered one of the main reasons for failure the experiments, because it soft and very sensitive rock.

The edges of the specimens are the most challenge, so most published papers have been shown different methods for extracting the specimen, part it was used lathe to get perfect specimen by dry conditions (Senseny et al,.1989), other part was used coring machine at speed reaching (100-150) RPM, accompained with compressive air for cleaning and cooling the coring head (Fuenkajorn et al,.1988).

On the other hands, most of specimens for this thesis have prepared by using coring machine with speed (750) RPM, but at wet condition, by using mist flow consist of salt saturated brine and compressed air, the mixture pressure (0.5 bar), while the hollow cylinder specimen was prepared by lathe.

After coring operation of the specimen, it should be dried by using oven temperature (70-100) C, and then to get two parallel ends for the specimen, by using grinding machine, see figure (5-1)

Figure 5-1 Coring machine, grinding machine, system to mixed (ssw) with air

5.2.2. Local measuring tools

The measurements of deformation internal or external under high pressure and temperature vessel are considered the big challenge for hollow cylinder specimen test.

For instance one of apparatus, that use LVDT to measure the deformation inside borehole of hollow cylinder but that will be at the expense of loss the ability to apply internal pressure, and keep just external pressure, as well the put all system under plane strain case (fixed two ends of specimen).(Elkadi et al,.2005).

The other apparatus has been followed same manner but the internal deformation, is measured by using strain gauges (Rahimi et al,.2015).Furthermore, other part that benefit from the change in volume of fluid inside borehole to get the deformation. (Ewy et al,1990).In addition, different apparatuses use internal measurement tool (pasted strain gauges on cantilever) (Papamichos et al,.2010). The yield surface is important to characterise a geomaterial, and it need different types of experiments. The volumetric strain is one of the traditional ways that should be measured.

On the other hand, the geomaterial do not behave, as isotropic material, which is sometime assumed to behave as transvers isotropic material, or an anisotropic, so, it need absolutely to measure the volumetric strain correctly. It's easy to measure axial strain by using LVDT transducer, while the optical devices cannot use as PIV because the difficulties related to applied pressure.

However, this thesis has been tried to open this door in order to open all designs, as can as possible. So, there are two options to use the Hollow cylinder:

Apparatus equips with PIV technique, and other to use internal measurement cantilever tool based on strain gauge.

A big challenge is the pressure and how to pass all electrics cables between two different pressures regions .All the improvements have based on strain gauges, a few articles that published have been shown different methods to measure deformation under high pressure (Feng et al,.2010), despite all of these have introduced a strip of stainless steel that using affixed strain gauges on both surfaces (upper ,lower) of each strip (full Wheatstone bridge) but on standard solid cylindrical specimen, see figure (5-2)

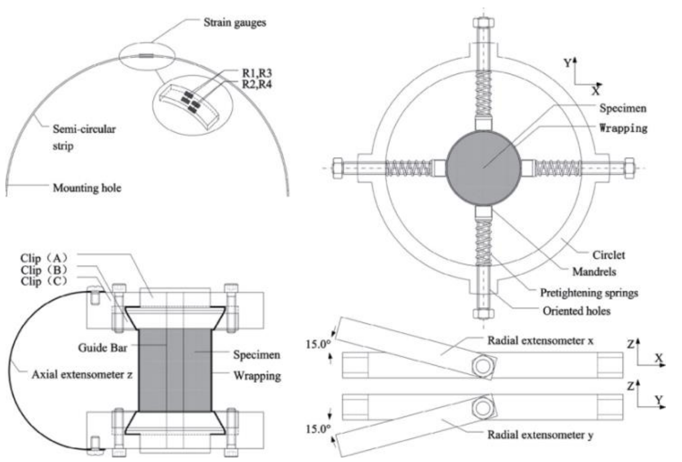


Figure 5-2 (a) Schematic of the extensometer elastic element. (b) Assembly schematic of the axial extensometer. (c) Radial extensometers fixture. (d) Assembly schematic of radial extensometers. (Feng et al,.2010)

The figure has shown a detail of triaxial extensometer, which is consisting of two parts:

One for axial displacement that has simple design , stainless steel strip (10mm width,0.3 mm thickness, 70mm diameter) .This strip has been connected on upper and lower parts of hydrostatic vessel ,that can measures the deformation into this strip by using four strain gauges (two in the upper surface ,and other two in lower).

The second part to measure radial displacements. It consist of a spring made of steel connecting to semi-circular strips(10mm width,0.3 mm thickness, 100mm diameter) to measure in x and y direction.

Both of these two radial strips are installed on a specially designed stainless steel fixture , which consist of a circlet , four stainless steel mandrels and pre-tighten springs, that able to accept the two strips in x and y direction

When the specimen was loaded, deformation in three direction was transferred to the three extensometers, then these extensometers were transferred the deformation to the strain gauges (due to bending of the strips). The smart idea on this design was used the structure body of apparatus to conduct the signals all electrical circuits, that was putting inside protected pressure chamber, meaning the power supply for measuring (12V) was connected in the piston, while the transferred signals were received by connect to the pressure chamber body, both two bodies was good isolated.

The same design, the cantilever –type local deformation transducer has been used also by (Yimsiri et al,. 2005) for tri-axial test of soil material, the benefits to use this type of devices, it's the cost compare with other LVDT transducers, because LTC-cantilever is homemade instrument which utilize strain gauges,

The device was designed to measure the axial displacement, which consist of two cantilever-LDTs are placed on the same vertical alignment but at different levels of a specimen to measure the vertical movement of two points on the specimen surface, The relative movements of these two points can then be used to derive the local axial strain .

The cantilever-LDT was made of a heat-treated phosphor bronze strip. The size of the strip was approximately 25mm length (only cantilever portion), 5mm width, and 0.35mm thick. Four strain gages (two on one side and two on the other side) were attached near the fixed-end of the strip to form a full Wheatstone bridge circuit, which offers optimum sensitivity and compensation of temperature , the strain gauges have resistance 120 **Ω** , and their dimensions are 0.84mm width and 2mm length, The free end of the cantilever-LDT was attached with a small cylindrical tube (1.0-mm diameter and 5mm length) to provide a contact point to a specimen see figure (5-3),

So in each side of a specimen, has pair of cantilever LDT. The average for two pairs has been extracted to get accurate measurement. The figure has shown the cantilever-LDT overcome the restriction that represented high strain.

This restriction is limited for Original-LDT, because the cantilever were pre-bent before the test, and when the deformation will be increased, it will be released against L-hinge, .while the Original-LDT cannot cover the strain deformation, when will be high., because it will be removed when axial strain 2%, because it will be damaged, here advantage of cantilever –LDT against Original -LDT

All the wires attached strain gauges were passed through the outlet at the base of tri-axial chamber.

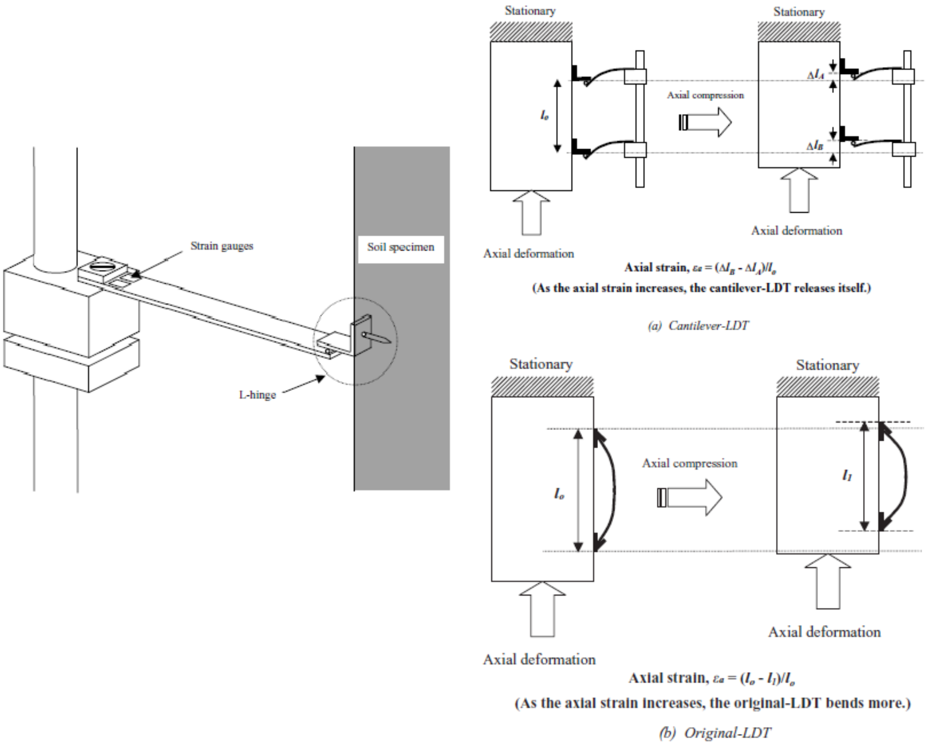


Figure 5-3 cantilever LDT (Yimsiri et al,2005)

To review more articles, experiments that were done to hollow cylinder of sandstone (Papamichos et al,.2010).

The measuring devices was used with these experiments, has shown in the figure (5-4) .These devices have been studied, because it has been taken the same design, here, but with lots of improvements.

Two pairs of cantilevers were used to this apparatus, which connect with outer cantilevers to measure the diametric deformation in two perpendicular directions, because with this configuration the internal pressure cannot apply, use the strain gauges on these cantilever. On the other hand, the measurement tools (internal, external) have designed in this thesis to use under two independent pressure regions, and they have used strain gauges too. Furthermore, the internal measurement device consists of four arms.

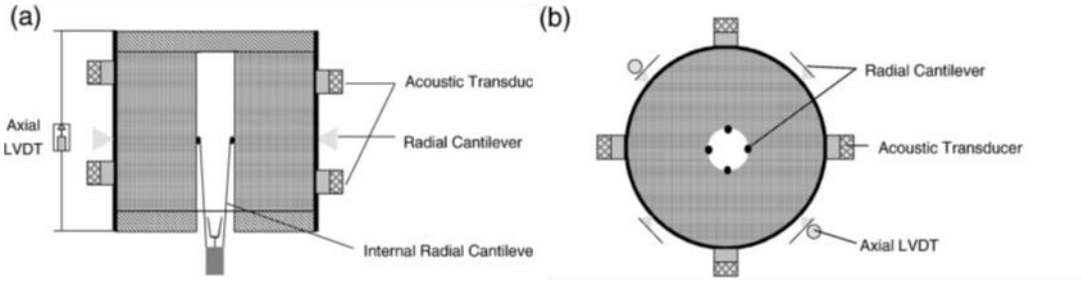


Figure 5-4 Specimen instrumentation: (i) two axial LVDTs, (ii) two external diametrical cantilever pairs, (iii) two internal diametrical cantilever pairs, and (iv) two acoustic emission transducers (Papamichos et al,.2010)

After this small introduction about some measuring devices which is used in geomechanical experiments, and because the Iraqi case studies require to do bench scale experiments to discover the reasons behind the collapsing casing, which mean the tools should withstand the temperature and pressure.

It should be meeting the creep test requirement to measure internal deformation for long periods

The new design of the tools have based on the cantilever idea and strain gauge too.

Different trials that have used here to reach the best design of cantilevers (internal, external); and the first prototype of this cantilever has created by simple materials.

So, the first hollow cylinder specimen is the Italian rock salt, and it has experienced under uniaxial creep test and it has used the prototype internal measuring tool, See figure (5-5).

Figure 5-5 measuring device for borehole deformation

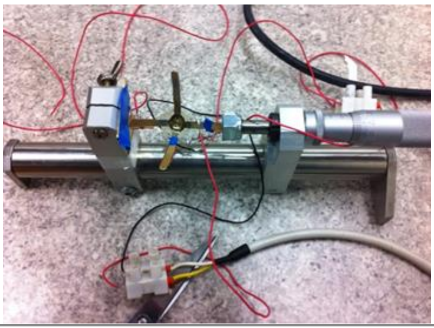
The elementary test to the hollow cylinder, is very important to design apparatus which give us the ability to reproduce the Iraqi case studies

The dimensions of the Italian specimen rock salt are (100 mm) outside diameter and the hole (45mm) , that have presented as base for designing two options of apparatuses; bore hole window apparatus and hollow cylinder triaxial test.

The prototype device consist of four arms, each arm made of phosphor bronze strip with length (30mm),width (3.5mm) and thickness (0.3mm), and on each arm has affixed strain gauge(120 Ω) .See figure (5-5).

Each strain gauge has connected to Wheatstone bridge, which meant quarter type .This type has been considered sensitive for temperature effect.

The calibration for this device has done by using micrometer (resolution 0.001mm), each arm has calibrated for (2mm), in two cycles to check the precision see figure (5-6).The strain gauge (4) graph has shown precision and good agreement with the strain gauge (3), while strain gauge (2) has shown small scaling error which its appeared usually when using spring or bending substance in measuring device. furthermore the strain gauge (1) has shown linearity error which generally that cannot avoid it in most measuring devices, because the first and the last reading are accurate, so meaning, there are not offset error, as well scaling error, but it can say this error come from using bending substance .Generally the calibration has shown good response for each arms. After calibration has done for each arms, attached the measuring device with hollow cylinder, and start the test.



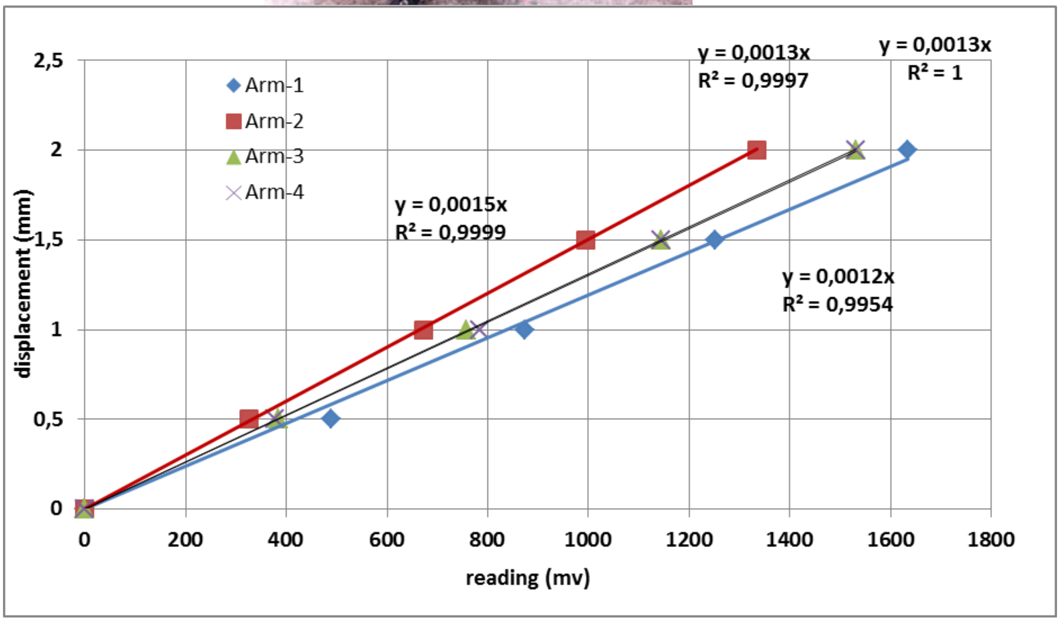


Figure 5-6 calibration of each strain gauge on each arm

The weakness of the internal deformation measurement device is thermal sensitive because it has created based on quarter Wheatstone bridge. So, the measuring device has made from solid brass (percentage of zinc are more than39% and 61% copper) the material will be high strength with low ductility at room temperature, the linear expansion of brass ($1.9X10^{-5}$ m/˚C/m)

The change in length that has affected by temperature, follow simple equation

$$\Delta L=\alpha.L_o.(T-T_o) \quad \text{.............(5-1)}$$

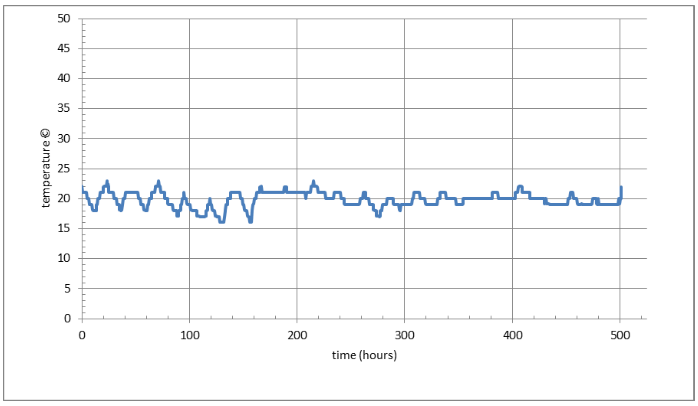


Figure 5-7 the temperature changing through long term creep test

The temperature changing has recorded during test period. See figure (5-7). As it has known, that the effect of temperature force the atoms in the material to be far from each other, and increase when the length of material increase too, however this change in length will not be too much, for instance if the temperature changing about (5C) as in our case, and if the arm has (100mm) long sample of the materials, the length will changes. See figure (5-8), so for our case the length of arms(30mm) the change of length from temperature change (5C) will be (0.006 millimetre) or may be less because the change of temperature most of time has not reached for (5C)

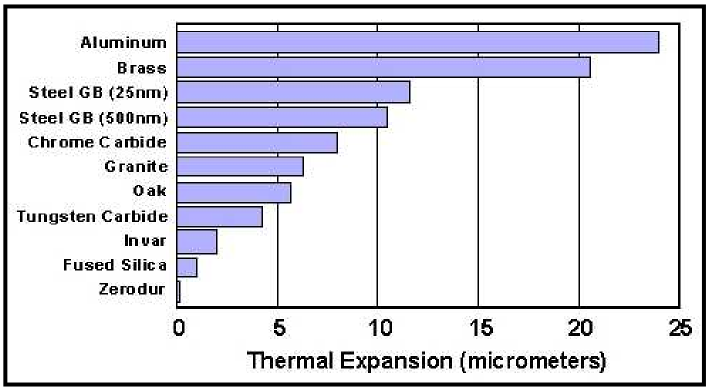


Figure 5-8 the change in length for (100mm) of each material when the temperatures change (5C).

Despite of restrictions the frame , especially for large diameter specimen (100mm), the experiment has done even the max load (1 MPa), the measuring device has set inside borehole and the position for each arm has been pointed. See figure (5-9)

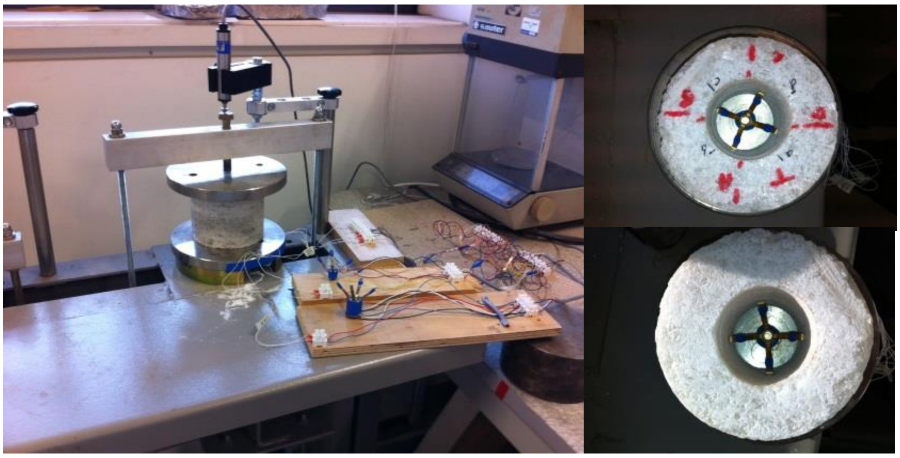


Figure 5-9 measuring device inside TWHC specimen

The test has started by applying (850 KPa) which has extended to (15 days) , and keep constant till (75 days), then was changed to the maximum load that the frame can support.(1MPa) till to the end of the test.

The target of the experiment is to determine the change in borehole during uniaxial creep test for long period extended for 6 months, and test the prototype of the internal measurement tool.

The internal deformation device has recorded for four points inside the borehole. It has been taken diameter between two opposite arms, it has been found the difference between the real measurement after the test and reading of device, for one side (16 micron) and for another side (30 micron), this difference, at the first time seem as big difference but it has expected because some factors have been effect:

1. The internal measuring device has not fixed in the bottom base of the creep loading frame.
2. It has not taken the temperature effect in recording

In general, it can be considered these differences accepted to the elementary test, because this is the prototype of the device. The improvements have been done for this device to overcome all obstacles'.

5.2.3. Mechanical detalis of the HC apparatus

The prototype internal measuring device has shown reasonable results. It has been benefit from space inside triaxial cell apparatus to pass all cables for this device. To connect two different pressure and temperature zones, its needed to design plugs which should be set inside triaxial cell and able to pass all cables, as well isolated the pressure. It has explained all details that connect with this plug (chapter 4).

All plugs have tested for pressure (30Mpa) and temperature (66C) for period not short.

The hollow cylinder apparatus has been created, based one triaxial apparatus space.

The following steps have been followed:

- Study all parts of tri-axial apparatus..
- Benefit from prototype internal measurement tool design.
- Review and modify all improvements which are needed for every period of time.
- Should be able to reproduce the case study conditions.

The new improvements that have been done which have shared others (published articles). However, the new hollow cylinder apparatus have ability to apply different stresses paths for long period time, and he has ability to measure borehole changing based on two simultaneous methods, (volume increments, two local measurement tools (internally, externally) .

It can be divided the HC apparatus into different parts as follow:

5.2.3.1 Upper part

This part consists of:

1. The upper pedestal, that contain conical concave gap to accept the conical convex knob .this design ensure that the applying load and the other parts of apparatus will be in the same vertical line with the specimen too.
2. The central platen that contribute with lower hollow part of the system for transferring the applied loads to the specimen, as well applied the internal pressure inside the borehole independently from axial and external pressure, and it has sealed circular pressure room which support the sealing pieces of hollow platen.
3. Hollow platen which consists of two pieces, adjustable metal piece conical furnished with Teflon piece to be inside inner membrane and to seal injected water as well keeping it inside this inner membrane and protect the rock salt specimen from any leakage of water. The other piece, it hollow metal furnished with four holes to accept bolts from upper central platen, which will be as the connection circle between central platen and the hollow specimen. See figure (5-10)

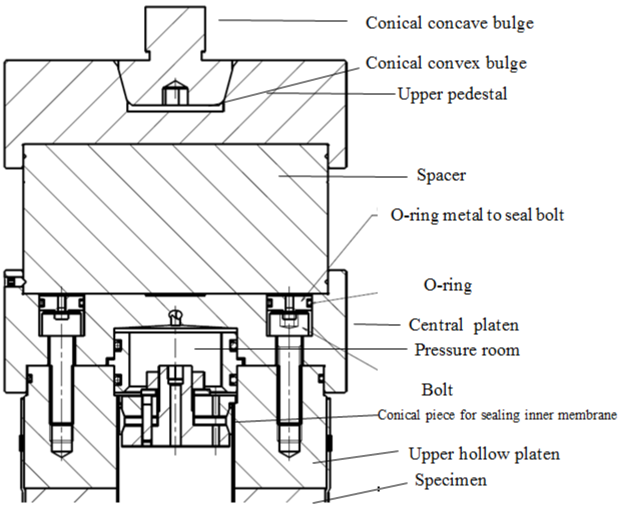


Figure 5-10   the upper part of HC apparatus

5.2.3.2 The hollow cylinder specimen

This part has to be with outer diameter (100 mm) and inner diameter (39mm), to be fit with lower and upper platens, as well to accept two types of membrane:

- Shrinkage outer membrane (FTP) or normal type.
- Neoprene inner membrane to protect rock salt from water by two different sealing methods for the upper and the lower parts, and it has able to let internal measurement tool to get the deformation of rock salt without any obstacles..

5.2.3.3 Lower part

This part consists of:

1. Hollow platen which has inner borehole, and furnished by O ring to seal the outer gap of the inner membrane to protect the rock salt specimen from any leakage of water from inside of the inner membrane. Also, it has been furnished with four holes to accept bolts from lower central platen, which will be as the connection circle between central platen and the hollow specimen.
2. The central platen that has been set on the lower threaded part of the system for transferring the applied loads to the specimen, as well complete the circulating system of the internal water pressure independently from axial and external pressure. It has been furnished with conical bulge to be set and sealed with hollow platen piece.
   Also, there are three sealed holes on this conical bulge, these three sealed holes to get passage for the cables of internal measurement device, also they connect with other three peripheral sealed holes to complete the passages towards oil environment. Furthermore, the conical bulge has place to fix the internal deformation device. Finally, there are four holes furnished with sealed bolt to keep hollow platen with central platen as one piece.

3. The lower pedestal threaded part that will be fixed firmly on the lower base of tri-axial cell. See figure (5-11).

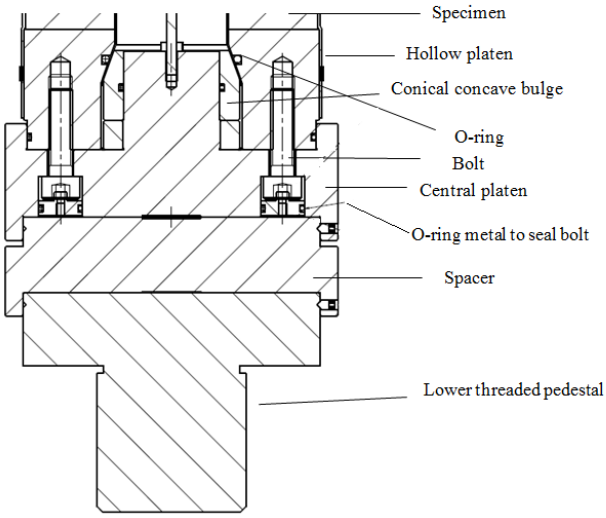


Figure 5-11 the lower part of HC apparatus

5.2.3.4 Internal deformation measurement device

This part has been improved for the first prototype design, which has used in the elementary uniaxial creep borehole closure test. The new improvements that have been done, consisting of

- String (D) that fixed on the conical piece of the lower part of the apparatus, and has been furnished by four places to fixed arms.
- Four arms (C) that can be replaced and fixed on the string by screws.
- Each arm accepts strain gauge (B) on its surfaces.
- Block (A) to fixed all arms .See figure (5-12)

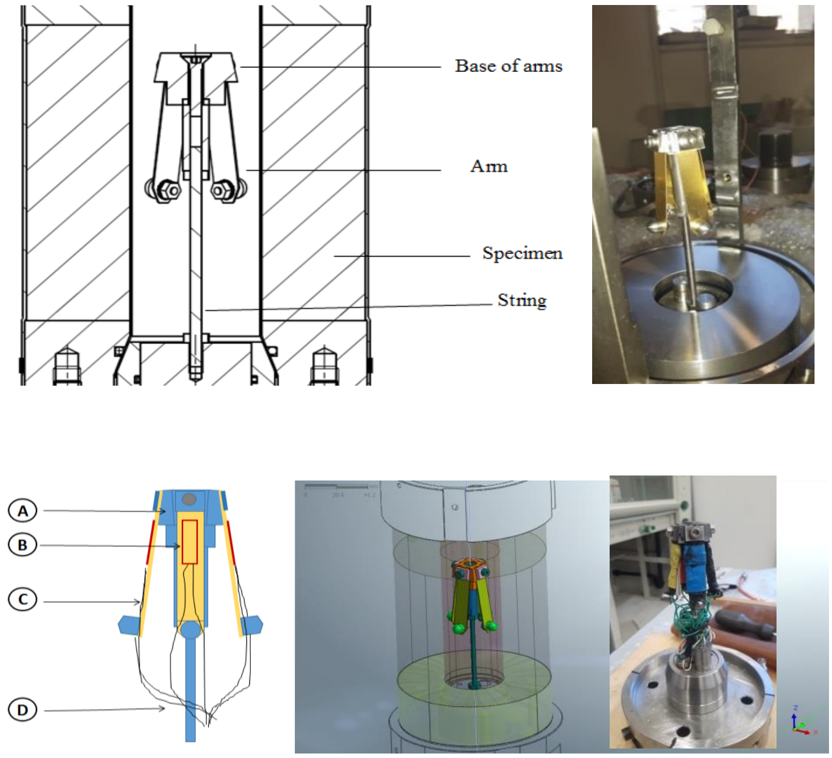


Figure 5-12 internal deformation measurement device

5.2.3.4.1.) Material of arm

To choose the best material that will be used of the arms, simple analysis of the beam cantilever has been done for maximum force that will be applied from arm to the inner membrane to be far from pinched, and be sure that the arm will not deform under the applied boundary conditions. See figure (5-13)

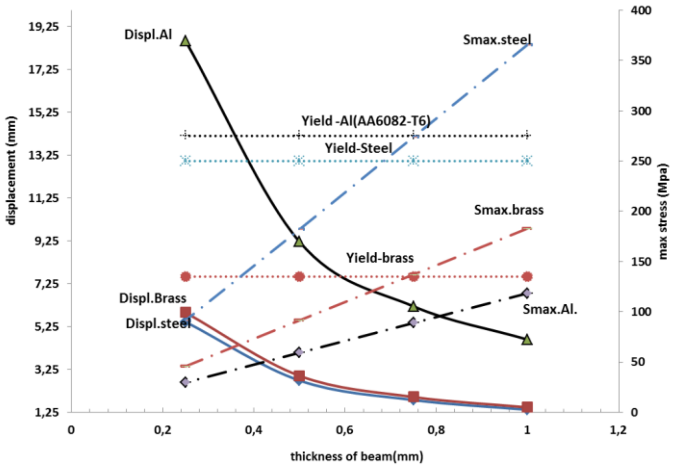


Figure 5-13 analysis for three type of material of arm internal device

The figure has shown clearly all materials can be worked with the boundary conditions of the rock salt even with different thickness but, the two best ,are steel and brass, because for thickness(1mm) of the arm , it can be reached for deflection (1.25 mm) without any problem for pinching of inner membrane. So, it has been selected the brass with thickness (0.4mm). This deflection are covered the deformation that expecting of the boundary conditions.

5.2.3.5 Centering system equipped with External measuring device, and safety system.

In order to be sure for applying vertical load on the specimen, it has been designed centering system, which consists of four pillars (B) that will be fixed into the lower part of apparatus. These pillars have been designed to accept two types of circular metal rings. One of them closed metal ring (E) for accurate centering while the other an opened circular metal ring (D), to allow the screws lock rings that used for insulation control outer membrane for vertical movements when the specimen will be experienced.

Furthermore, the safety system also equipped with it, by fixed four restrictions blocks (F) on the peripheral upper part of apparatus, exactly on the central upper part, these block have adjustable screws for tolerance. See figure (5-14).

Figure 5-14 centering, safety system,

5.2.3.6 Membrane (inner and outer)

It can be divided the membranes which have been used here into two parts:

- Outer membrane
- Inner membrane

The outer membrane, is shrinkage membrane (FEP 100 mm 2:1)(Geo-Shrink , ADTEX, heat shrink, fully recovered thickness 0.5 mm)(shrinkage temperature 110C, working temperature 200C, melting temperature 260C) which, can support high pressure and temperature, furthermore it can keep the specimen of hollow cylinder to be in the same axial direction with other two parts (the lower pedestal, and upper pedestal).

Due to the restriction of vessels' space around the specimen and a lot attachments with apparatus, the care should be taken when shrink the outer membrane. The procedure to shrink this membrane ,need to warm the specimen as well the membrane itself, before starting with shrinking process. Furthermore, this process might be effect on the specimen of the rock salt, because heating the rock salt has caused expanding it, which leads to falling some weaker bonding grains. Furthermore it should be protected the shrink membrane by remove the groove between the two pedestals (upper and lower) to the rock salt specimen by using slice of smooth brass (0.01 mm thickness), (200 mm width).

The inner membrane (39 mm diameter X 150 mm length) (0.3 mm thickness) (Neoprene) (Polychloroprene) (3.5-20.6 Mpa tensile range) (-46 to 121 C temperature range) (ASTM D-2000 Classification: BC, BE). It should insert to the lower part (conical base) as well should be adjusted to be fit with the upper part sealing (Expandable sealing piece) because the sequence of processing is necessary. For instance, if the inner membrane put incorrect position in the lower part, then set the lower pedestal which should be fixed with the lower part of apparatus by four bolts, the upper part sealing will be incorrect position too, and should repeated assembling process.

The key points in sealing process, two different mechanisms have been designed for this apparatus. There is a gap that has already put in the design for lower part because two different inclination surfaces that restrict the inner membrane in this gap, and allows to applied axial load without any limitations. One the other hand, the upper part sealing mechanism depends on pre mechanical applied force to inner membrane (D) to the inner diameter of the upper pedestal (E). “Ogive” its’ the name of this part, which consist of three pieces (upper (A), and lower steel parts (B) that restrict Teflon ring (C) between them).When tights the two pieces for each other expand the Teflon ring into inner membrane .See figure (5-15).

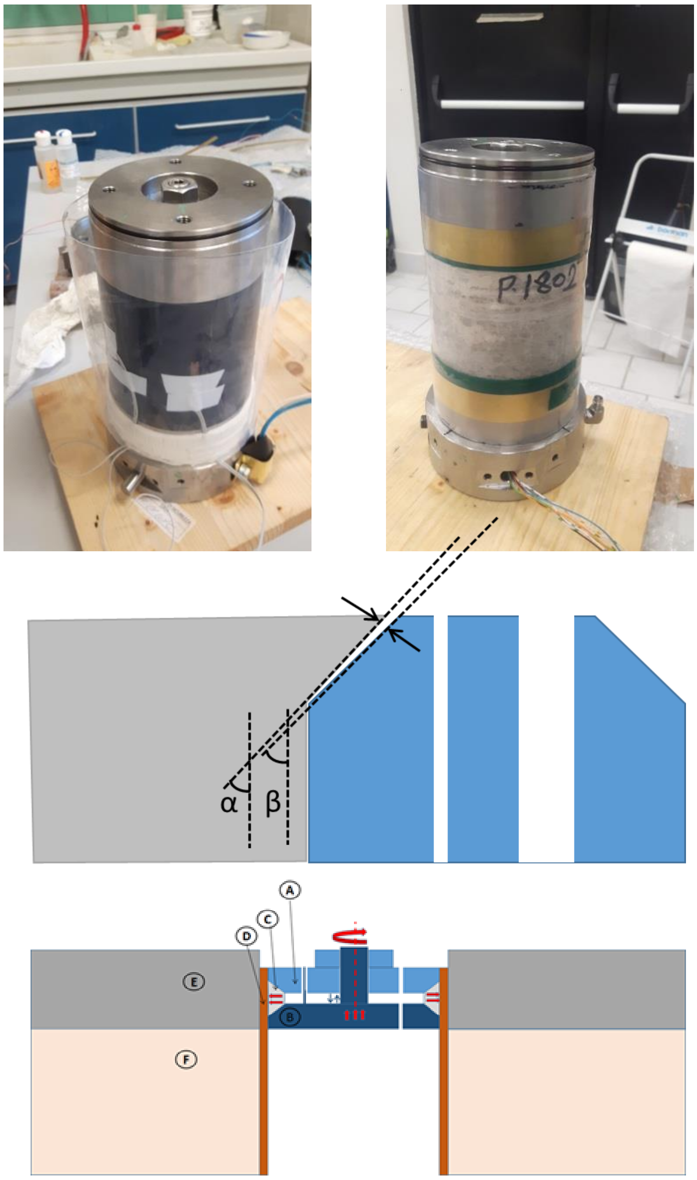


Figure 5-15 shrinkage membrane for two specimens (dummy, rock salt) (upper) mechanism of inner membrane to the lower part (middle), upper part (lower)

The important care should be done into the sealing of the upper part. It should be disassemble all parts before put the upper pedestal. The lower steel part should be set on the block of the internal measurement tool, Insert the Teflon ring into the inner membrane, after that put the upper pedestal on the rock salt specimen, finally should collect all parts the "Ogieva piece" and press the two steel parts to expand the Teflon ring against inner membrane .See figure (5-16)

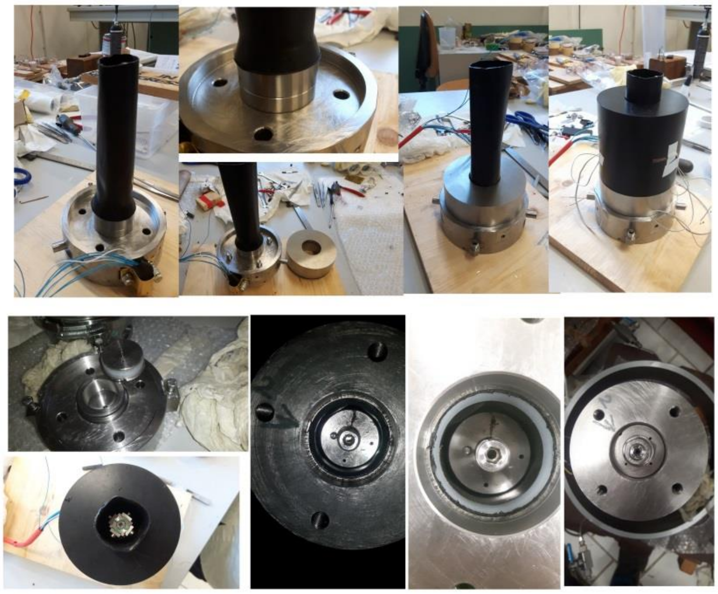


Figure 5-16 assembled inner membrane into lower part of apparatus (upper side), installation expandable sealing piece into inner membrane for upper part (lower side)

5.2.3.7 Small plug support 8th cables

it has been designed two types of plugs, large plugs which support 10cables (external plug),and small plug which support 8 cables. The plugs here which equipped with the hollow cylinder specimen should be modified to be fit with the small space inside borehole of the hollow cylinder, in order to give a good space for accessories of the internal measuring device. This plug should be inserting in the hole of the bottom base. The lengths of this plug (30 mm) with diameter (9mm), and should not to be more length because the restricted space inside borehole, which meant critical quantity of resin to withstand pressure and temperatures. Mixed resins through this restricted volume of the plugs(internal) to support isolation of 8th cables. The resins have distributed as followed from ambient (room temperature) to (66C temperature):

- Two compounds resin (Hock cell).
- Two compounds resin (Araldite A, B).
- Two compounds resin (Araldite 2014).

The test has done by using small pressure vessel, and equipped by temperatures bands. See figure (5-17).

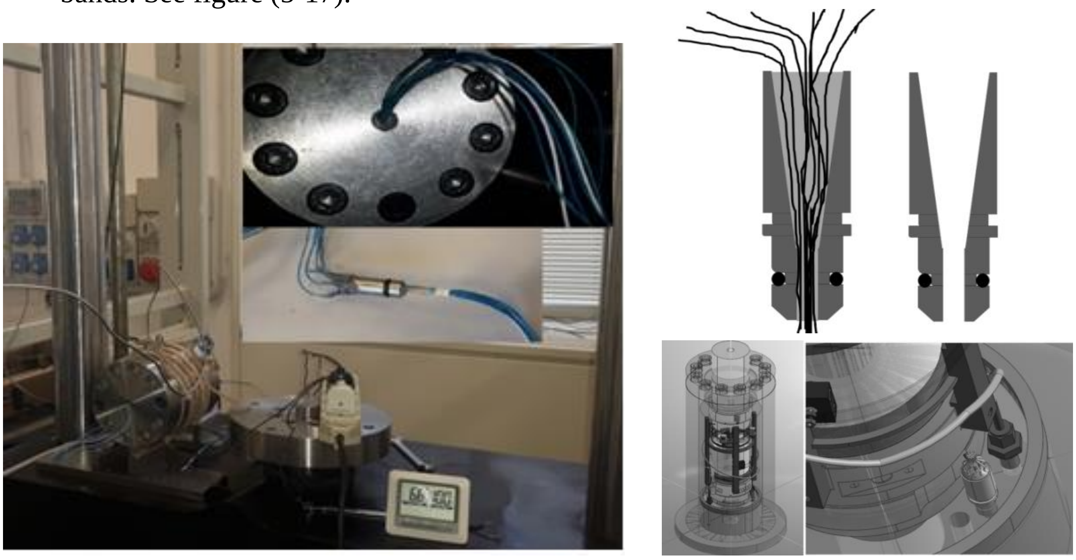


Figure 5-17 pressure vessel equipped with temperature bands for plug test

The pressure has been increased steeply till (30Mpa), and then increased the temperatures till reached (66C), for more than 3 hours without any leakages. See figure (5-18).

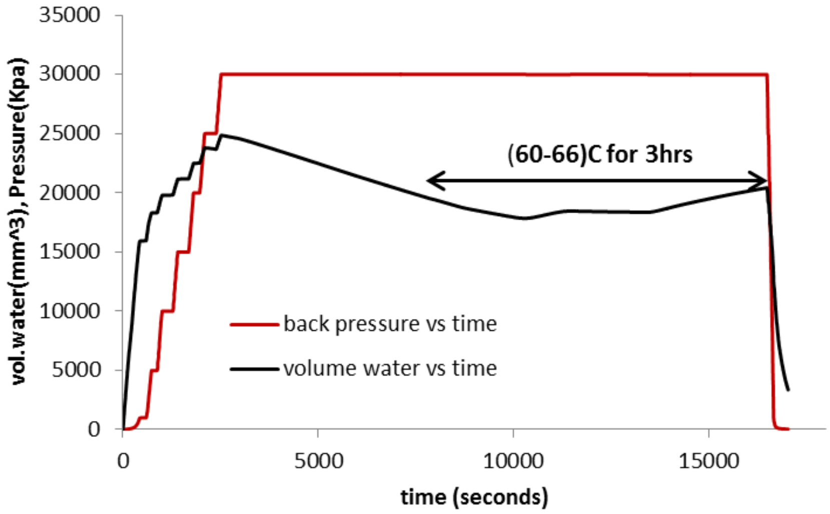


Figure 5-18 pressure and volume change vs. time for plug test

5.2.3.8 Protected way for cables (brass tube)

These improvements have been done to solve the connection between two plugs where located in different places of the lower part for the hollow cylinder system. The improvements design have done because using the maximum numbers of cables passing through one plug (8^{th} cables) despite the restrictions of small plug (9mm X 30 mm).However the system has been furnished by other two ports that can be used also to pass the cables, if the sealing problem has been still with those numbers (8^{th}) of cables of one small plug, by distribution those (8^{th}) cables on other ports, which is meant, each plug can be passed (2^{nd} to 3^{rd}) cables to give more volume for adhesive materials.

It has been used tubing brass that has dimensions, (8th) mm outside diameter and (1.5th) mm thickness which connected directly between lower parts hollow cylinder port and the vessel base port using sealing plugs (330mm length). See figure (6-16). This solution gives to continue with experiment even, if it will be faced some leakage from inner borehole instruments (plugs, cables, and seal). So, using this improvement, has given confident, that the leakage will be outside the vessel not inside the vessel and be far from problem to contaminate the oil with water. See figure (5-19) .The figure has shown the test operation of these improvements under 30Mpas, and the complete test.

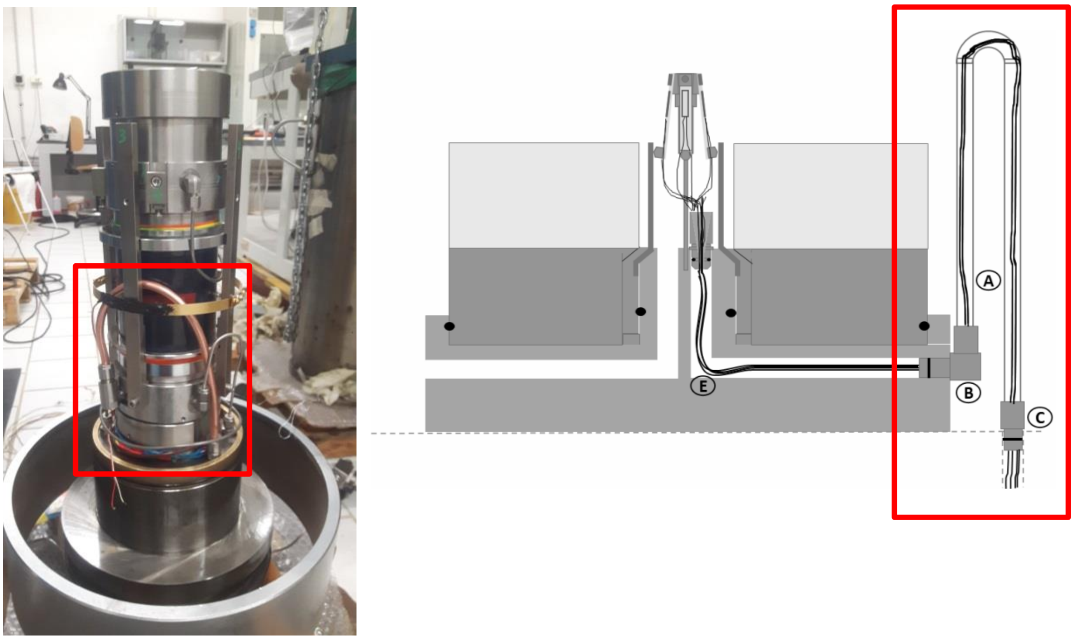


Figure 5-19 protected passage for connected cables (brass tube)

5.2.3.9 Local external band cantilever tool

It has been done second test for Italian rock salt using Hollow cylinder equipment's, but with additional accessories which has tested under high pressure (30Mpa) and temperature (60) successfully. These accessories have included the last improvements for external measurement tool.

The new design of the external measurement tool, has been done by manufacturing a half circular strip of brass (0.5mm thickness, 1 mm width, 220mm length), which was used the concentring system pillars' to suspend the driving system. This drive system consists of shaft, spring and small block equipped by bearing bushing to accept the shaft. The spring drive the shaft to be in touch with outside diameter of the specimen, to transfer the diametrical deformation of the specimen to the brass band cantilever, which is restricted between two driving systems.

Two external bands cantilevers have wrapped the specimen to get the deformations in two opposite points in the middle of the specimen. See figure (5-20).

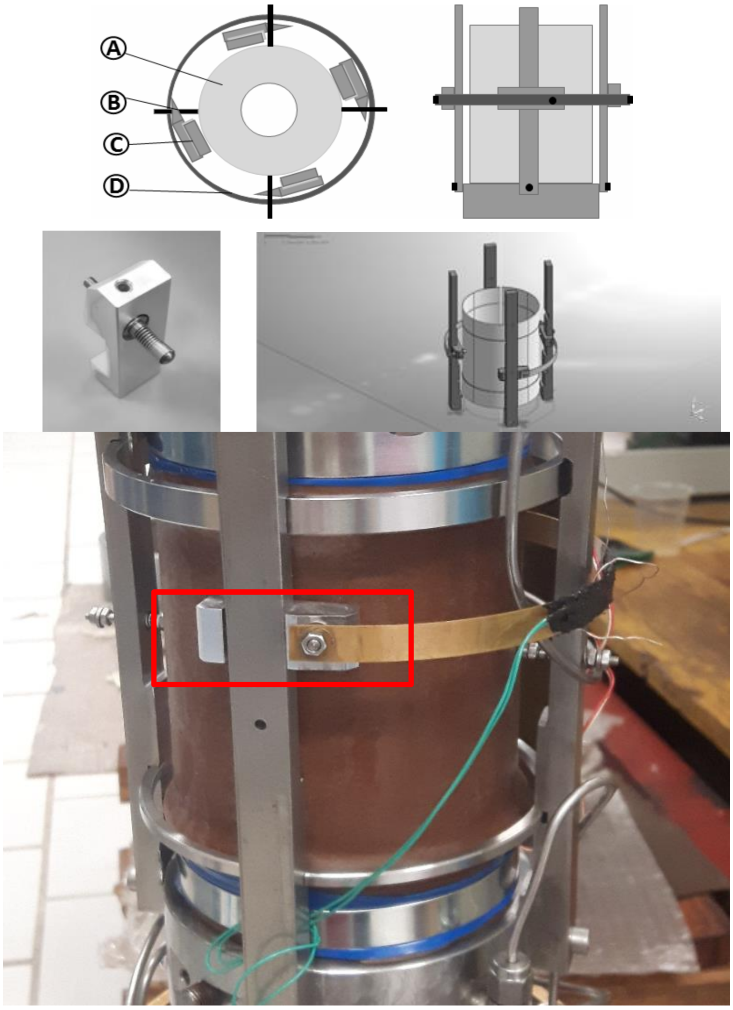


Figure 5-20 Improved external local measurement band cantilever

5.2.4. Calibration tests for the HC apparatus

The first step that should be done before used this apparatus, should be tests in the same boundary condition, the target of test to be sure all sealing parts work well. Its important test and the material that has selected to be under this boundary condition is Delrine. This material has mechanical properties to withstand the boundary conditions and stresses paths that has planned to do it for rock salt. It has characterized with good dimensional stability, low moisture absorption, high fatigue endurance, high strength and stiffness properties, superior impact and creep resistance, chemical resistance to fuels and solvent and good wear and abrasion properties.

5.2.4.1 Test procedure

The main target of this test to be sure, that there are not communication between two pressure system, internal (water) and external (oil), because the plugs which contain all cables have been tested and checked well. So, all passages for cables were being blocked by solid plugs internally (water system) and externally (oil system).

The installation steps as follow:

- Fix the inner membrane on the lower conical part of the central platen for the lower part.
- Fix the hollow platen on the central platen with four bolts.
- Insert hollow cylinder Delrine specimen (100X39) mm into inner membrane.
- Fix the hollow platen of the upper part on the upper part of the specimen.

- Adjusted the conical sealed piece into the inner membrane with hollow platen of the upper part, then force this conical piece to expand in order to get the sealing of the water system
- Connect central platen with hollow platen by tighten the four bolts and insert the sealing cover of these bolts.
- Cover the specimen with external membrane, and fixed the steel bands.
- Put all parts on the base of the cell, in order to install the centering system.
- Connect the fluid tubes for water with the upper and lower fitting elbows.

5.3. Borehole windows apparatus(BHWA)

The other design apparatus which, is not manufactured because the time limitation. So, it’s just put the idea which has tested by numerical codes (chapter one). The new design here, it can be used PIV technique to measure the deformation inside borehole, then it will be far from any ports for cables or strain gauges, also far from internal LDT, because this design has been completely depending on the glass which has designed to close the upper and lower parts, hence it can be used directly PIV technique to measure the deformation of the specimen boreholes’.

In the same context, this is not the first time that is used camera with geo-mechanics experiments. It was designed apparatus; this apparatus was equipped with camera .This camera set inside the borehole of TWHC specimen (Hashemi et al ,.2015).See figure (5-21).

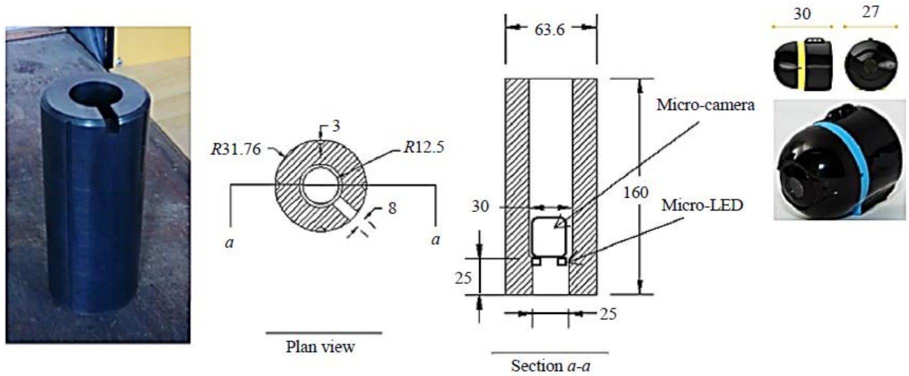


Figure 5-21 the top and bottom platens and camera with led (Hashemi et al,.2015).

However, it cannot be used internal pressure through this apparatus because it was used Hoek cell; as well the borehole windows apparatus can apply just external pressure in 2D plane strain. The camera will be fixed outside to measure the deformation on the upper face or even in the lower.

5.3.1. BHWA parts

The interacted parts into the borehole windows apparatus are two glasses which are represented the windows, sealing pressure rooms, and other steel parts. It can apply pressure externally by connected pump unit. The specimen should be thick wall hollow cylinder (salt), farther it can be seen the interaction between casing and rock salt. Its mean, can be mimic lots of boundary studies.

Despite, the main task for it to simulate the interaction between borehole and casing pipe, but it can be used to do the experiment without casing too.

The key parts here are the two thick borosilicate glasses which fixed on top and bottom of salt specimen. These glasses can support pressure up to (60Mpa) and connect with other steel parts by sealing compounds. The other part is the stainless steel frame solid which has elastomers and room to apply pressure on outside diameter of the salt specimen.

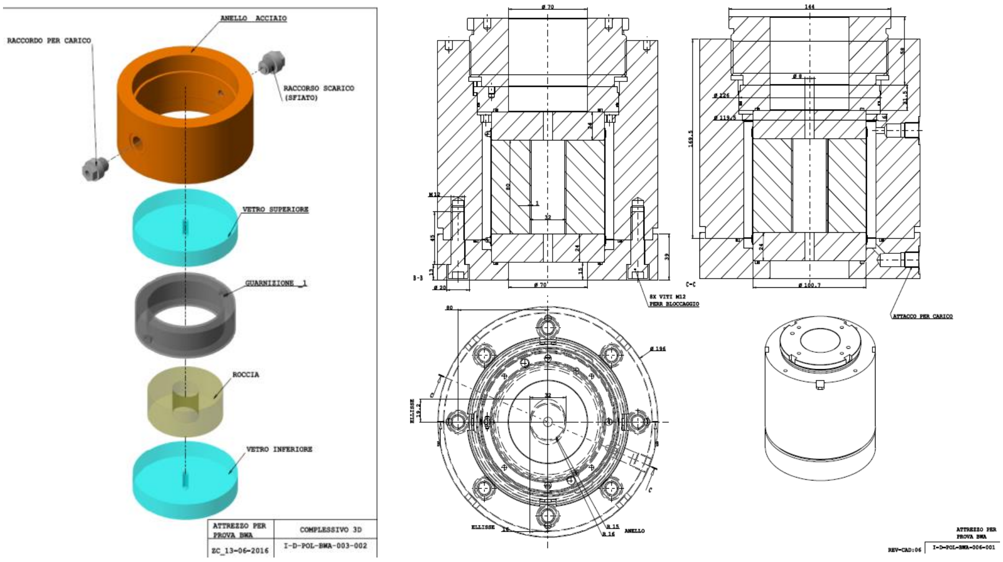


Figure 5-22 Borehole windows apparatus

This apparatus accept to use the internal measuring device to measure the deformation inside the borehole, besides using strain gauges, as well the PIV technique. See figure (5-22).

The main advantage of this apparatus too, it can be used other internal or external measurement tools beside PIV.

Chapter 6: Experimental results of the new hollow cylinder (HC)

6.1. Elementary uniaxial creep test of HC

6.1.1. Borehole closure under uniaxial compressive creep test

Despite the limitation of a frame creep test, especially for large diameter specimen (100mm), the experiment was done by applying the max load (1.1MPa) the prototype measuring device was set inside borehole and the exact position for each arm has been pointed, in order to check the reading by it with real state, as it has shown in the figure (6-1)

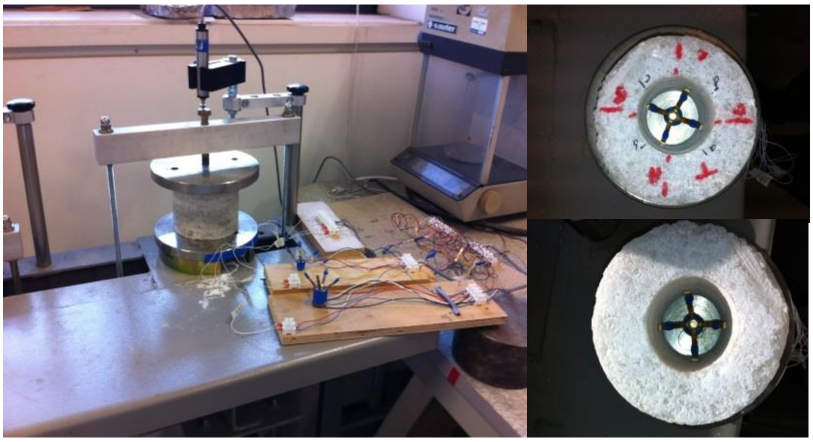


Figure 6-1 uniaxial creep tests equipped with measuring device inside TWHC specimen

The load distribution through this experiment has been shown in figure (6-2). The test was started by applying (850 KPa) which was distributed on (15 days) , and keep constant tile (75 days), then was changed to the maximum load that the frame can support.(1.1MPa) till to the end of the test.

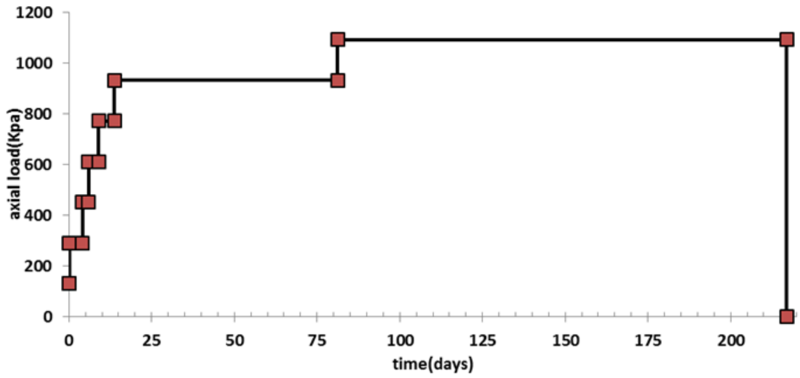


Figure 6-2 history load for uniaxial creep test of TWHC

The test has shown normal creep behaviour which the hollow cylinder responding directly when the loading changed, however, some responding especially after the last loading (75 days), might be because shaking into the loading frame. See figure (6-3).

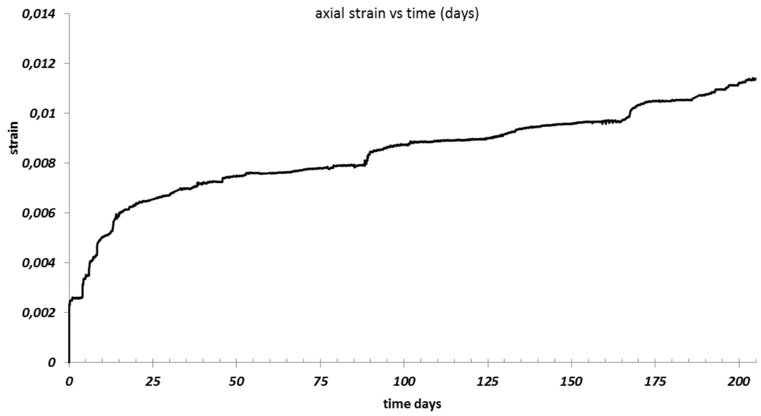


Figure 6-3 axial strain vs. time of TWHC uniaxial creep test.

In order to evaluate the Italian rock salt, at every loading changed the rock salt has been responded by increasing strain rate but later this behaviour extend with the previous loading stage till, the steady state creep was begun after (75days), after periods of transient deformations, at axial load (1.1 MPa), it was expected behaviour because low loads without confining pressure the most deformation has been happened by micro-mechanics processing. See figure (6-4).

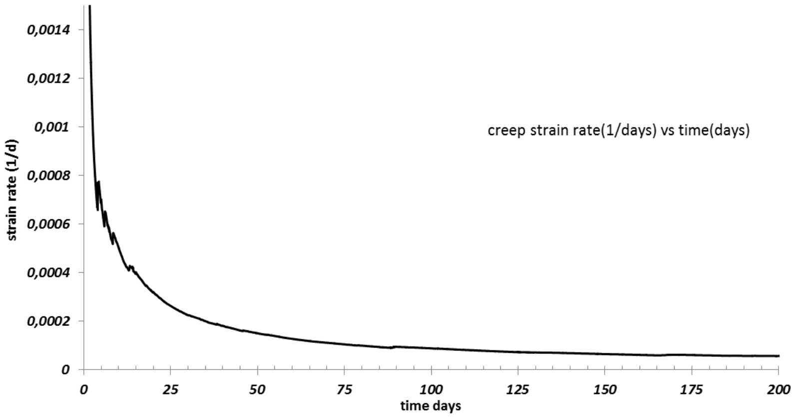


Figure 6-4 strain rate vs. time of TWHC uniaxial creep test

The rock salt has shown transient deformation starting with (1, 72x10^{-8} S^{-1}) and the last strain rate when it was steady was (6.5625x10^{-10} S^{-1}).

Furthermore, the targets for this test actually, to test the prototype internal device. The deformation in both sides has been measured by this internal prototype tool, which has shown different deformation for each arm, but the reading has calculated for each two opposite arms reading, and it has compared with actual deformation that has done in the hollow cylinder specimen. It has found the difference between the last recording and actual measurement for one couple of arms (0.03mm) while the other couple was (0.016mm), so the results are encouraging because it can measure the deformation in different parts in the borehole of the hollow cylinder specimen .The general trend was good comparison with simple design. See figure (6-5). The figure has shown same behaviour for each opposite arms (c6 and c8) for instance, while the other opposite arms (c5 and c7).

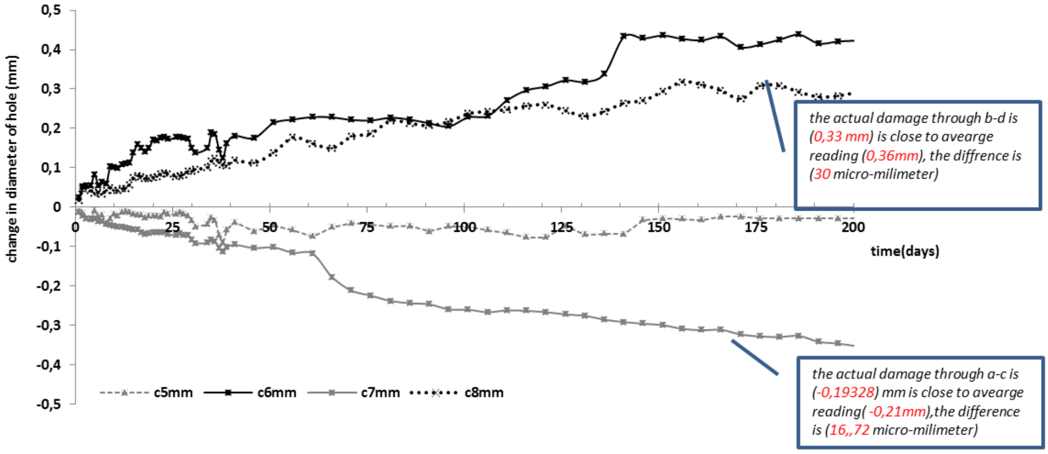


Figure 6-5 internal borehole closure device measurements

It should be evaluated these creep curves from type of creep point of view, so the strain rate for each arms was recorded and plotted vs. time .See figure (6-6) .The general trend for all arms have shown transient creep ($9.29x10^{-9}$-1.15 $x10^{-8}$) S^{-1} till reaching 50th days, after this date the trend of strain rate convert to steady state creep (1.27x 10^{-9}) S^{-1}, and all arms have stability read till the end of the test, however the arm(5) has been recorded less deformation compare with the others. Its mean, three arms have been shown in compression trend and approximately the same trend and values of creep strain, on the other hand, one arm was shown less deformation, the reason might be the internal measurement tool has not affixed in the center of pedestal. See figure (6-7).

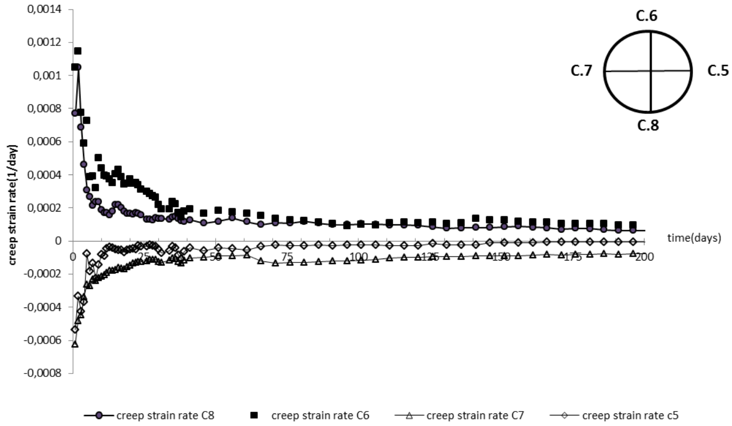


Figure 6-6 strain rate for each arms vs time of TWHC creep test.

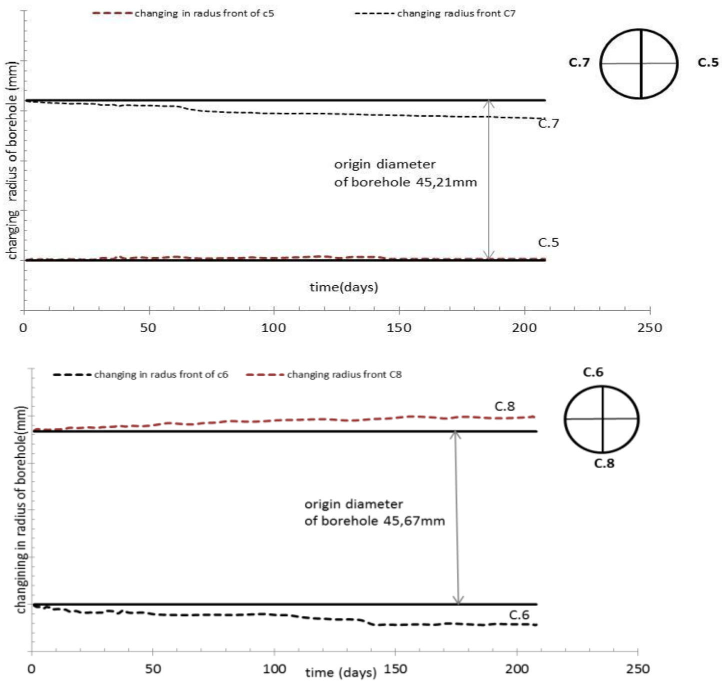


Figure 6-7 arms measurement compare for reference diameter for TWHC creep test.

Generally, as it has mentioned in chapter 5, different reasons have been played behind these reading differences

1. The position that was recorded the results, was approximately between the mid of specimen and the bottom sides, and the real reading after tests, that has registered, it has taken in the edges of borehole.
2. The internal measuring device has not affixed in the bottom base of the creep loading frame.
3. It has not taken the temperature effect in recording

But in general, it can consider these differences are accepted for the first elementary test, and it can improvement the performance by fixed the internal measuring device in the base of the frame, inside the borehole before starting the test, as well, it can be coating the device with some Teflon material to protect them from temperature change.

On the other hand, along the internal surface of borehole of the specimen, the deformations have occurred in different way, for instance part of the in situ condition tri-axial creep experiment was done, and equipped with two points of measuring inside the borehole, one under 0.25 meter from the top of the borehole, and other under 0.5 meter of (1 meter) depth of the borehole. The first point was shown less deformation (1-2) % lower than the second point (Fuenkajorn et al ,.1988).

Those were for tri-axial creep test, while in our case uniaxial creep test with lower axial load, so, might be it has correct measurement of this arm because different deformations patterns of borehole have been shown, depending on stress path which was being applied.

In brief, the hollow cylinder uniaxial creep test with low axial loads has done in order to test and improve the prototype internal deformation device; because these type of experiments (in situ condition) or boundary value problem experiments have been effect by size effect, degree of homogeneity, geometric boundary, and difference of stress field.

6.1.2. Elementary borehole closure under tensile test

The borehole closure test under tension condition was not done at the first time, because it has been tried to establish constitutive model for creep from tensile strength (Wisetsaen et al,.2015). As it's known, most of experiments are focused on compressive strength because this feature can show clearly the behaviour of deformation, if a loading rate of strain rate will be changed ,the behaviour of the deformation change also, and other factors effects directly on this behaviour ,as temperature that decrease the compressive strength when it will be increased.

At the same time, that has improved and modified accessories of the equipment's, it has planned to test borehole effect of the Italian rock salt under tension condition, and study the tangent stresses which create first crack along the tensile loading, and has planned also to use PIV techniques to measure the displacement around this borehole because, it has studied to develop BHWA apparatus (borehole windows apparatus),

This apparatus has designed to use the glass through construction, for that reason through this test, the glass has put between the camera and the specimen. Unfortunately, the camera has light movement during the test because it has not fixed well. The results have not depended from PIV point of view; however, the results have been given good impression to use the glass in design, as it has explained in the chapter 5.

As the available data was just axial displacement, so it was calculated the tangent stresses along the loaded diameter of a rock disk with a centre hole by (Jaeger et al,.1966)(Hudson et al ,.1969)

$$\boldsymbol{\sigma_\theta = \frac{2PKF}{\pi DL}} \quad \textbf{......................(6-1)}$$

$$\boldsymbol{k = 6 + 36 * (^{ri}/_{ra})^\wedge 2} \quad \textbf{......(6-2)}$$

The ratio between borehole diameters to the specimen diameter has been played big role for determining the tensile strength, because the tensile strength actually is an experimental property and not a material property. It was mentioned that the variety caused by three factors (the probabilistic nature of tensile strength, failure initiating but not propagating and the calculated stress is not the real stress (168), and the strength tensile is constant when this ratio more than 0.2, which was meant the hole into the specimen do not have any effect, however the compressive part from horizontal stress will be effect. See figures: (6-8), and (6-9).

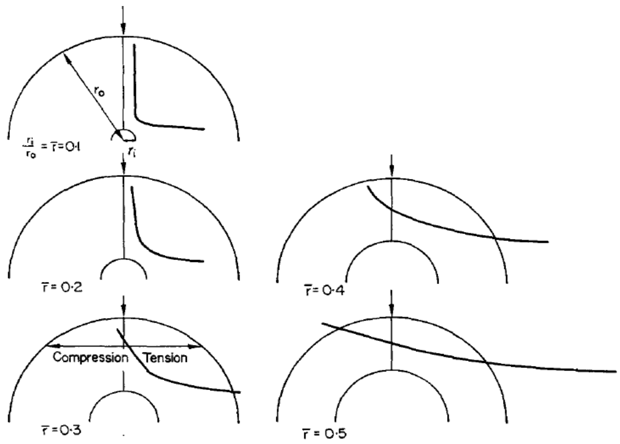


Figure 6-8 Magnitude of horizontal stresses along vertical diameter in the ring test (Hudson et al,.1969)

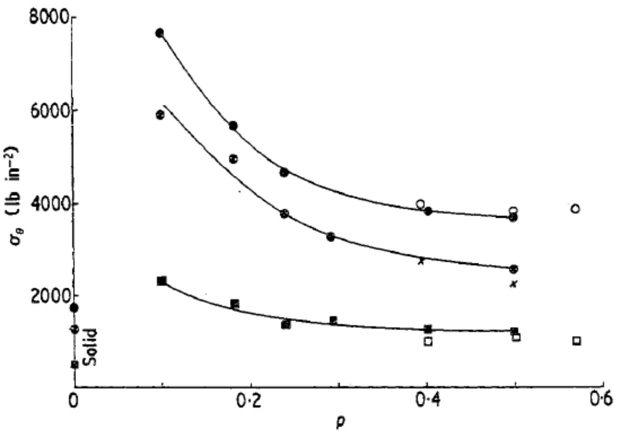


Figure 6-9 the variation of calculated tensile strength at failure with (ρ=a/b) for Trachyte (full circle) external load, internal load (open circle), marble (cross in circles) external load, marble (crosses) internal load, sandstone (full square)external load, sandstone (open square) internal load ring test (Jaeger et al,. 1966).

The Italian salt tensile behaviour can be studied and compared with tensile strength of other rocks, because the ratio of inner to outer diameter is between (0.1-0.2), so it can be expected high tensile strength value (9.2 MPa) compare with (1.5 MPa),even the thickness of the specimen was not standard because it's bigger than half value of the diameter. See figure (6-10)

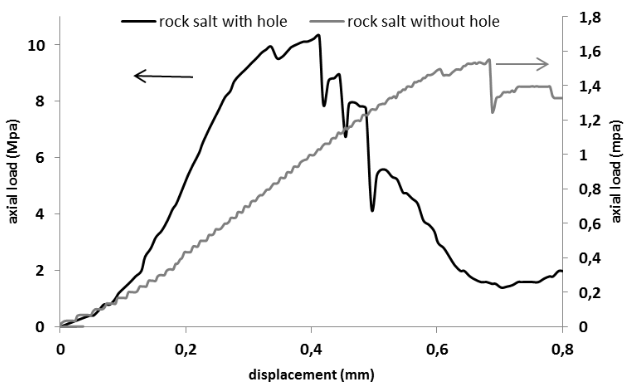


Figure 6-10 Italian rock salt behaviour with hole and without hole.

6.2. Calibration for HC: tests results without internal measurment tool

The target of the test is to verify all sealing parts of the apparatus; the test has done by closing all ports in the lower part by plugs, as well to get idea for behaviour of volume change inside the borehole ,when will be under boundary condition (in situ , drilling and creep stages).

It can be seen the loads distribution for external, internal and axial stresses .See figure (6-11).

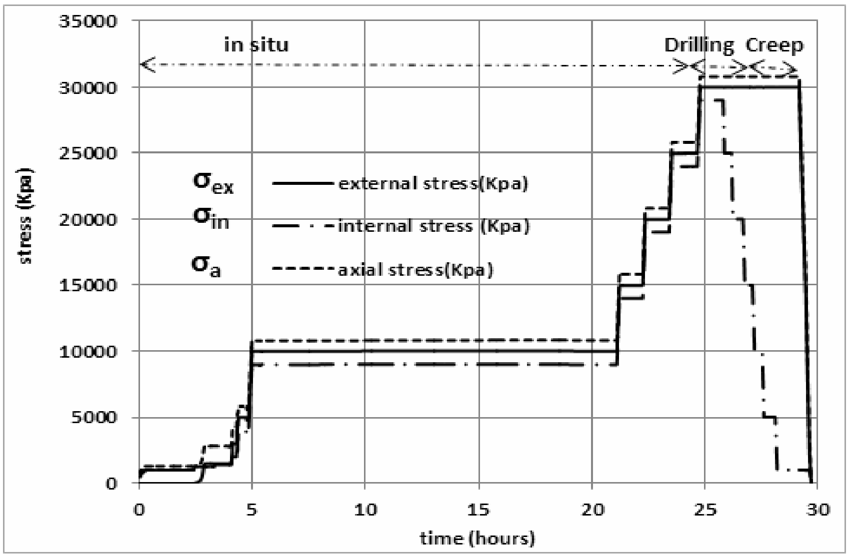


Figure 6-11 stresses distribution for Delrine HC test.

The figure has shown, the stages of the boundary condition for the Iraqi case study, starting by in suit stages applying (30 Mpa) internally, externally and axially stresses, then drilling processing that the borehole wall has exposed to the devaitroic stress (5 Mpa and 10 Mpa), and finally the creep stage. This stage that has simulated the effect of the creeping in the borehole due to the effect of devaitoric stresses (15 Mpa, 20 Mpa,25 Mpa and 29 Mpa). These stresses changes during different stages of the experiment have distributed around borehole wall that can be seen in the figure (6-12). The figure has shown the stresses changing around borehole during three stages of the test, specific creep stage, which shows ($\boldsymbol{\sigma_\theta > \sigma_r > \sigma_z}$). These stresses changed in the borehole wall effect directly on the volume water change inside the borehole which can be seen also in the figure (6-13), that has shown also the volumetric strain based in water change in the borehole of the specimen during three stages with internal stress.

The way that can be checked sealing processing, the volume changed increments during the three stages have followed, in specify the drilling and creep stages. See figure (6-14)

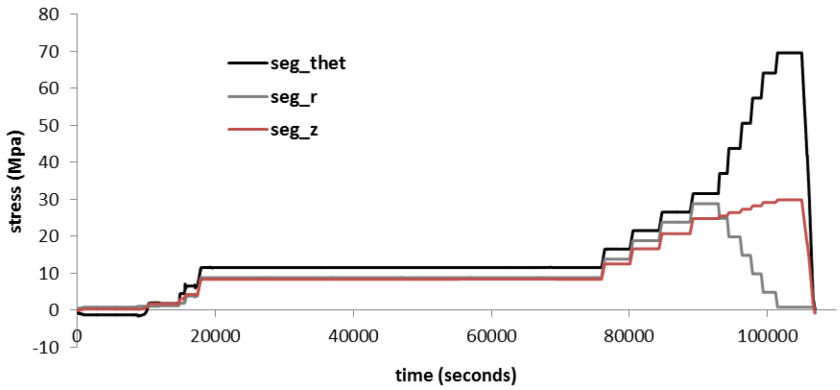


Figure 6-12 stresses distribution around borehole for the test.

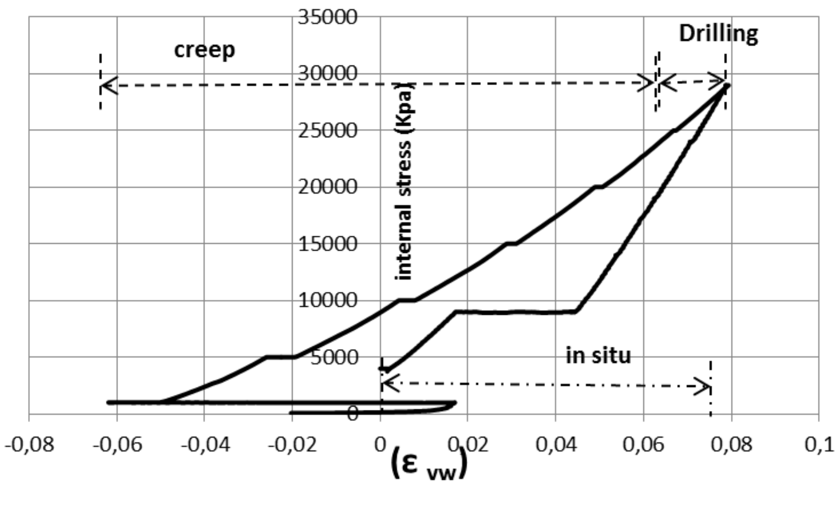


Figure 6-13 external and internal pressure vs. volumetric strain.

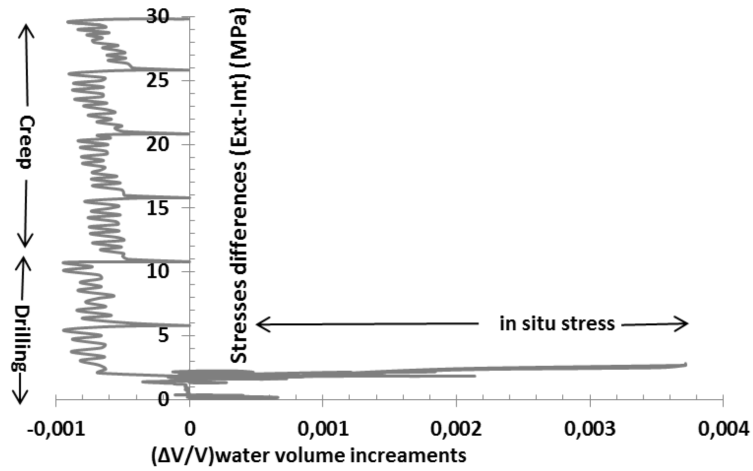


Figure 6-14 increments change of water volume vs. differences stresses.

The three stages of the test have been affected on the borehole and axial part of the specimen from geomechanical point of the view, after the success of the verifying sealing parts of the apparatus. Both borehole and axial displacement have been changed during the in situ stage, by the same trends ,even the borehole of the specimen have shown expanded by (1.35 mm) , while the axial displacement compressed by (0.2 mm). On the other hand, the two stages (drilling and creep) have shown closure in the borehole by (1.75 mm). In the other words, the expanded in the borehole through in situ stage, have been recovered when the stresses difference (25 Mpa), then keep closure till (-0.4 mm), while the axial displacement have followed the same trend (compression) but with less rate till (0.3 mm). These effects has shown the figure (5-15) and distributed this effect can be seen in the figure (6-15). The figure has shown the relation between stresses difference (external and internal stresses) with borehole change, which has shown also 30% of bore closure, happened at the drilling stage, while 70% at the creep stage, even the material (Drelin) is different on rock salt but it give us good impression for general trend.

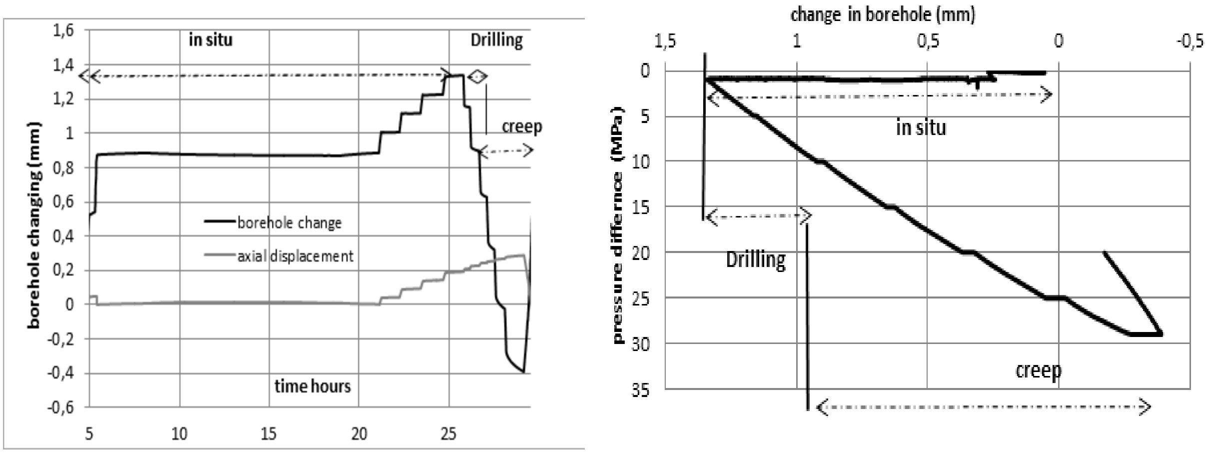


Figure 6-15 changing of borehole &axial displacement with time, and borehole change vs. pressure difference

6.3. Calibration for HC: tests results with internal measurment tool

It has been done another test for the TWHC Delrin, but with internal measurement tool and that demands to use the modified plugs ensuring passages for all connected cables with the internal measurement tool. Some improvements have been done in order to reduce the numbers of plugs that withstand between two different pressure environments by increasing number of cables for each plug, (8-10) cables and it has been created protected path for all connected cables to be outside the cell from high pressure region, using brass tube . The target of this test, to be sure the system work well under temperature and pressure conditions, which should do for rock salt. The parts were tested as follow:

- Internal measurement tool response.
- Cable connection and isolation.
- Improvement that has done for passage cables (brass tube).

- Outer and inner membranes sealing.

6.3.1. Results of the test

After the small plug was tested under high pressure and temperature at pressure vessel, as well the tubing brass, the complete test has done to check the ability of the internal measurement tool for the boundary conditions. All (8th) cables that connecting between the internal measurement tool and data log that passed through tested small plugs, should be passed carefully through brass tube to avoid damage or scratches.

External measurement band tool as well thermocouple to measure temperature inside the vessel pass through other plug to connect with data log.

It has tried to check all parts carefully through this test, starting with in situ stage by increasing external, internal and axial stresses to (20 MPa).Different stages of calibrations have been done to get a good comparisons between borehole closure measurements based on internal tool and the measurements based on water volume changes. Then the external stress has been increased till (30Mpa), and part of test was done under temperature effect (40 c) too. The stresses distributions for the tests can be seen in figure (6-16).

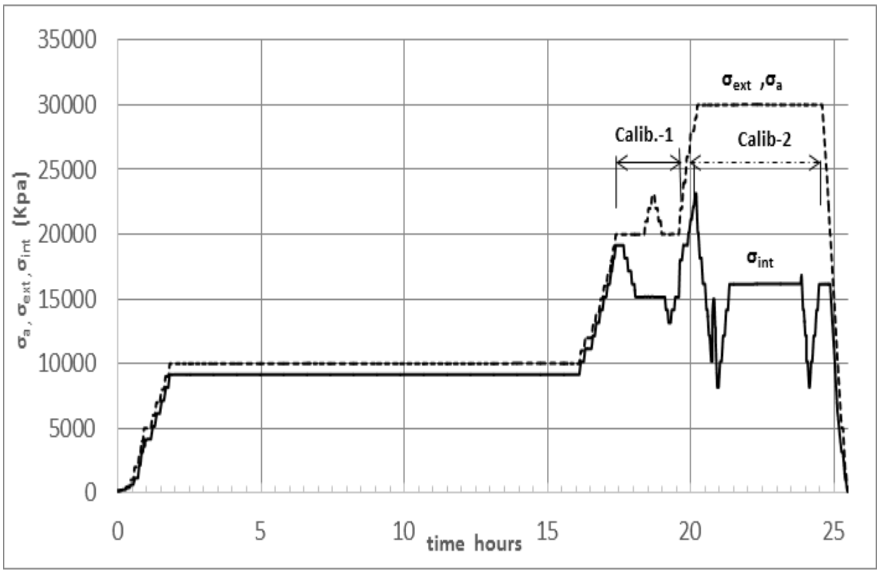


Figure 6-16 stress distribution for the 2nd verification Drelin HC test

Increasing and decreasing the internal pressure by same steps under fixed external and axial load to test the reversibility under room temperature, after that it was increased the external pressure till (30 Mpa) and fixing the internal pressure, later increased the temperature till (40 C) and other calibration have been done too at this temperature. The comparison between the two measurements (water, internal tool) for the 2nd calibration can be seeing through the figure (6-17). The figure has shown clearly the accurate measurements can be taken from the internal tool, because the measurements based on water have been affected by the materials inside the borehole as inner membrane material, cables, and resins inside the plugs.

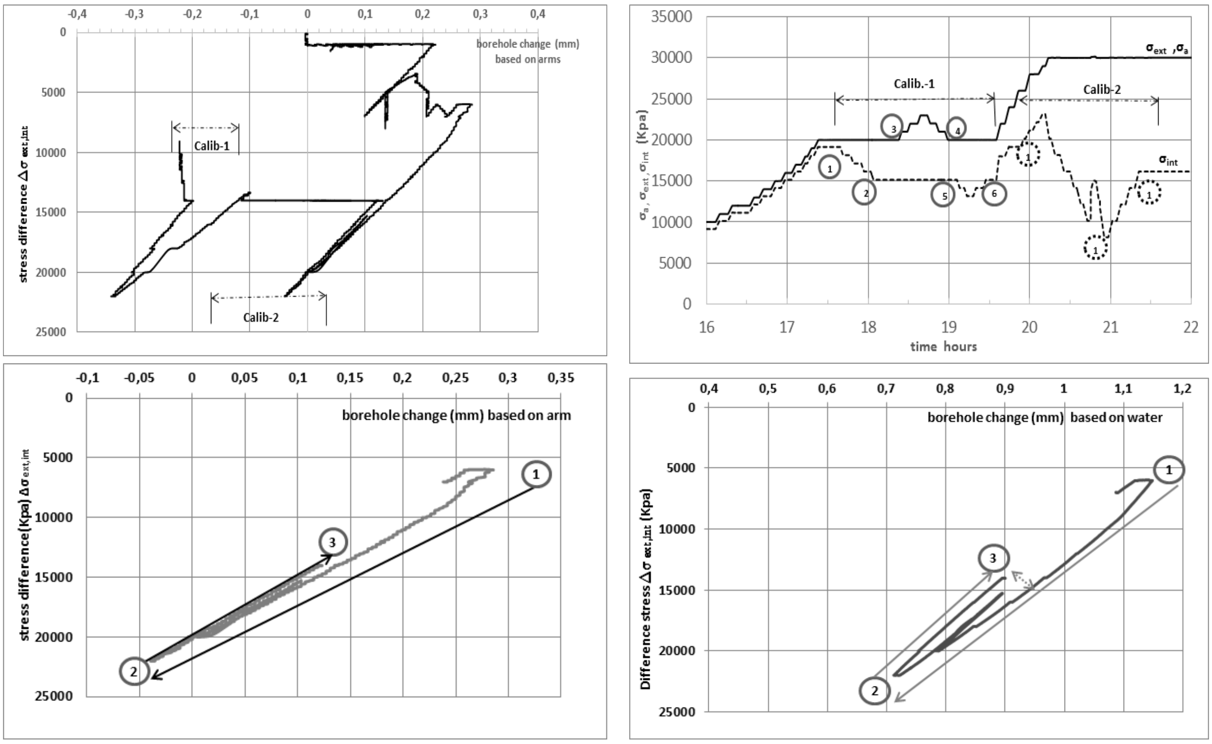


Figure 6-17 Comparison between two borehole measurements bath for HC - Delrin test

The hollow cylinder specimen test gives wide variety to do any type of test because the principles stresses can move due to changing of external, internal and axial loads. The main distribution stress paths depending on the position of tangential, radial and axial stresses state than can be calculated using elastic theory. So, here, it can be shown the decreasing the internal stress has not affected to the outer diameter of the specimen while this effect is very clear in the borehole wall, however, any small change of external stress will effect directly on the specimen. See figures (6-18). Thus the dimensions of the specimen are compatible and support all planned stages (in situ, drilling, and creep) from geometry point of view.

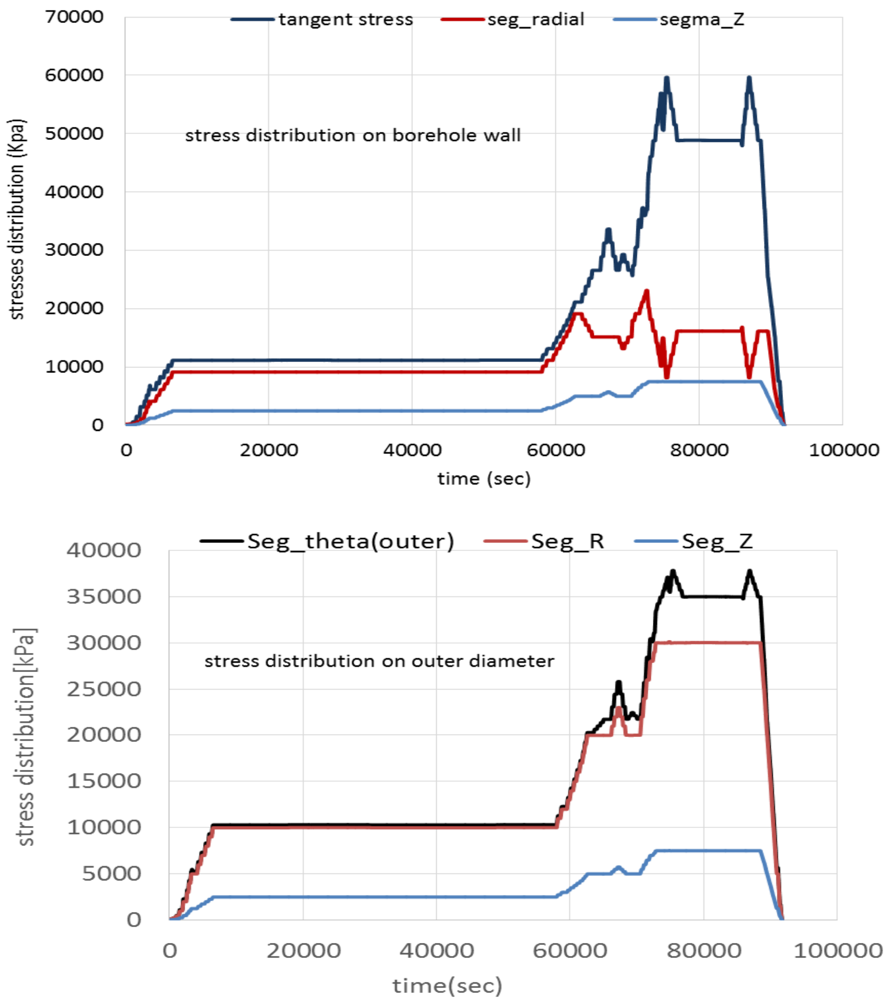


Figure 6-18 the stress state of tangent, radial and axial stress in the outer boundary of the specimen (upper), and in borehole wall of the specimen (lower).

It is clear the behaviour of both radial and tangent stresses are high in borehole wall and less value in the outer boundary responding to changing of the external and internal pressures. Generally, the state here, tangent stress is the main stress, which bigger than radial, and axial, if the specimen is rock rather than Delrin, the failure which is expected, will be shear failure with low echelon as it has mention in chapter two.

The behaviour of internal measurement tool for these changing for every sides of the borehole can be seen in the figure (6-19).

All four arms have generally shown the same trend responding for changing of external and internal stresses as well temperatures. It's clear the arms (2) and (3) have shown same responding, while the two arms (1), (4) have steeply changes but reflected the same trend of other arms, that expanded through in situ stages, and when external stress increasing at fixed internal stress. On the other hand , all of them have shown reduction in borehole through drilling and creep stages, but with different values (1 mm),(0.25mm)(0.4mm),for (arm4),(arm1),and (arm2+arm3) respectively for calibration 1.

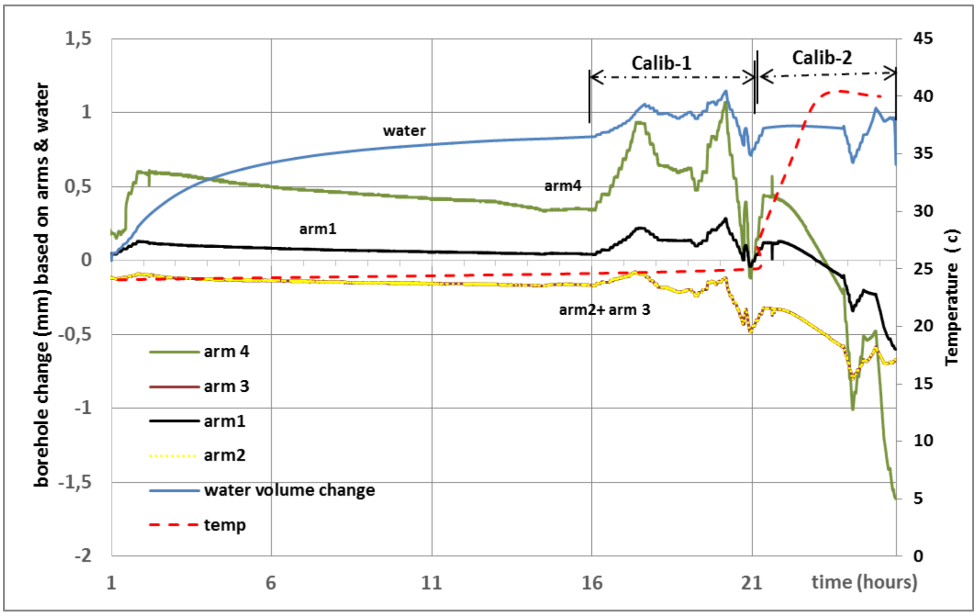


Figure 6-19 , borehole diameter responding to external and internal pressures changing measured by internal tool.

However, all arms have responded with the same trends when temperature increased (40C), also, the figure has shown the arm (4) is close to the measurement based on water. Furthermore, the external measurement band has shown the same behaviour responding for both temperature and pressure difference too, by compression through in situ condition (0.01mm), and expanding during drilling and creep stages (0.03mm) . See figure (6-20). The figure has shown also, this tool is very sensitive to temperature change too.

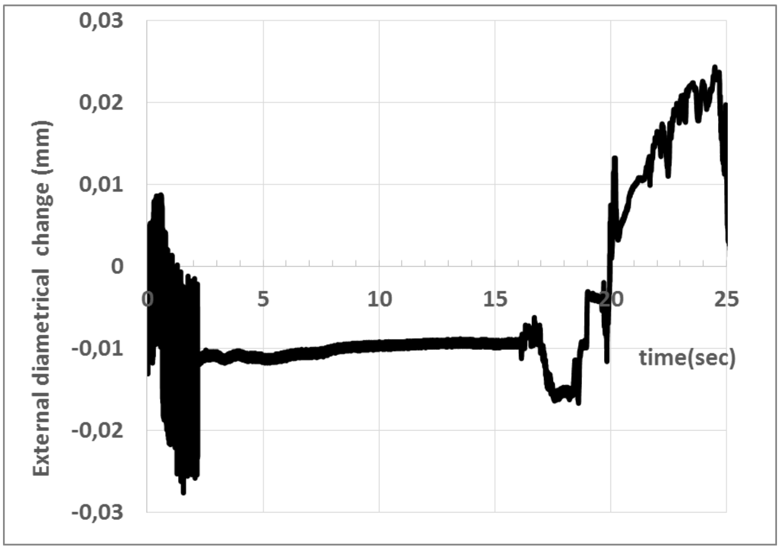


Figure 6-20 external measurement band trend

As results, the test has achieved:

- The temperature has affected clearly for both measurements tools.
- It can be simulate all case study state with this apparatus (30 Mpa).
- All sealing parts have worked well during good period.

So, it has been do calibration for parts of local measurements tools by loading pressure (30 Mpa) into (12 steps) and unloading with same steps at (25C), and then the temperature has been increased to (55C), and repeated loading matrix , in order to calibrate tools. See figure (6-21). It's very clear, the temperature effect on the local external band tool by (2.25 mm), and compare with one arm of local internal toll by (1.2 mm).

At the same calibration test, it has been study pressure effect too, for external local band tool; this effect reach to (1 mm), while in the arm of local internal tool has just (0.2mm). See figure (6-22).

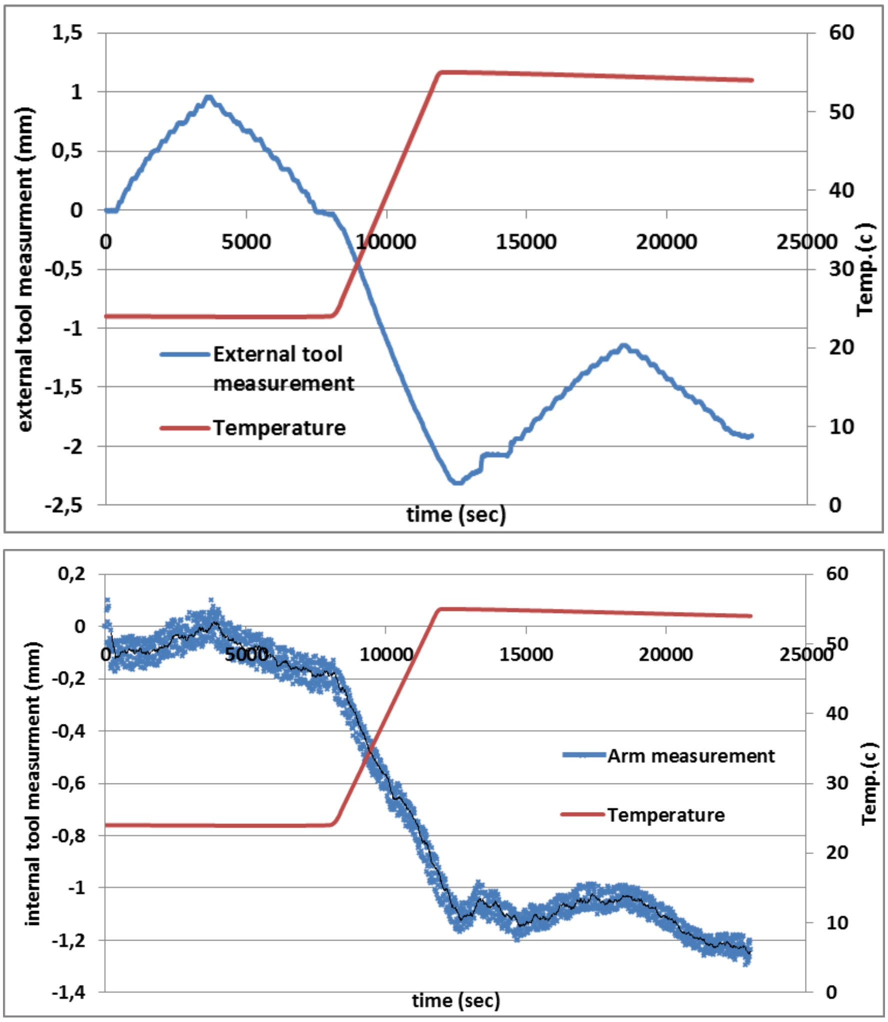


Figure 6-21 Calibration for temperature for arm of internal tool (upper), for external band tool (lower)

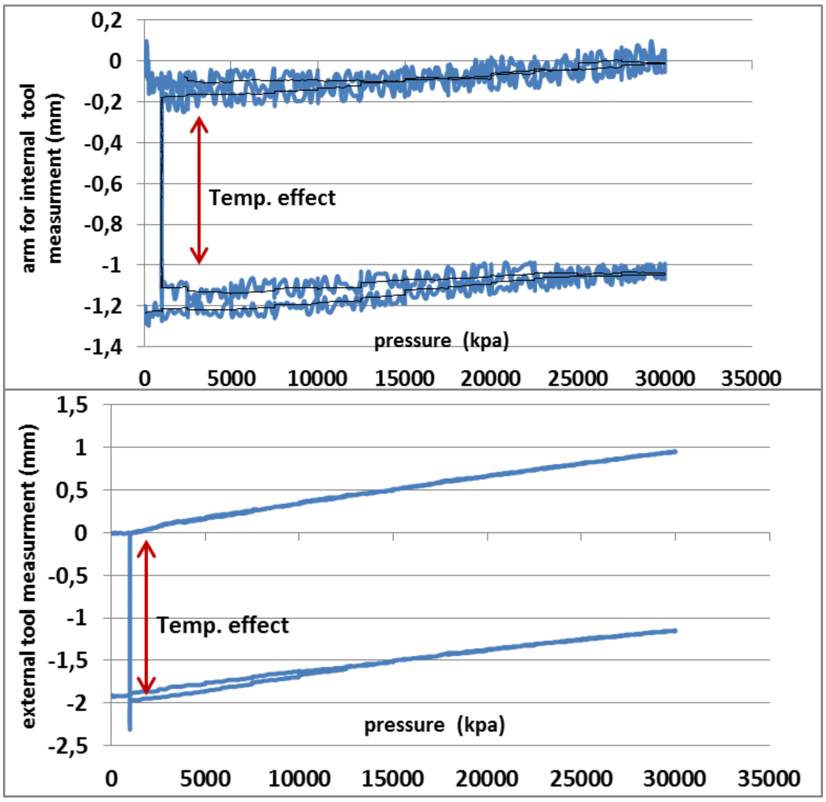


Figure 6-22 , pressure effect on the arm of internal tool(upper), external band tool(lower).

6.4. Test results for HC: Italian rock salt

6.4.1. First test : HC_IT_RS#1.

After, different types of the improvements that have done due to more experimental tests for material (Drelin), the first test with Italian rock salt hollow cylinder specimen has prepared by creating (38.6 mm) borehole on this specimen using lathe machine. New calibration has done for the new configuration of cables that connected between affixed strain gauges on arms and (GDS.Lab.Inc) data log through Whitestone Bridge. See figure (6-23).

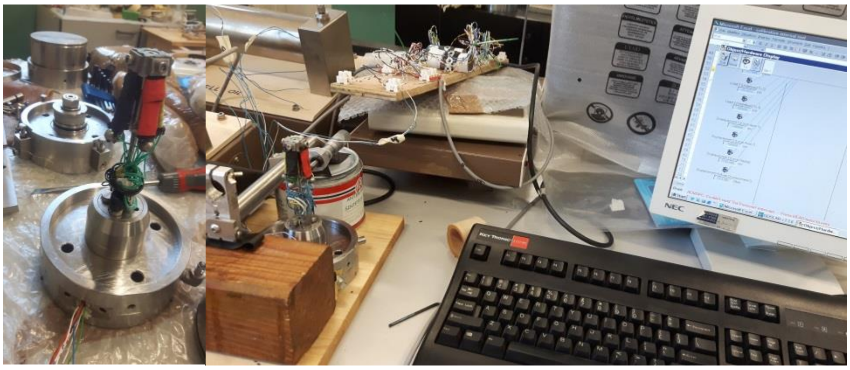


Figure 6-23 calibration for every test of internal measurement tool

Assembled all parts of TWHC apparatus following the procedure that has mentioned before, and in order to benefit from the injected water volume on borehole as another check way for measuring tool, the test has done under (20 Mpa), and (45C) temperature as the previous test that has used (Drelin) material. It can be simulated the in situ condition of the Iraqi case study in laboratory as bench scale experiment.

The test can be divided for two part, that represent the in situ conditions, and drilling operations which affect in the borehole at range of deviatoric stresses extending between (1 Mpa -10 Mpa). The general stresses paths for applied forces and stress distribution can be seen in figures (6-24), (6-25).

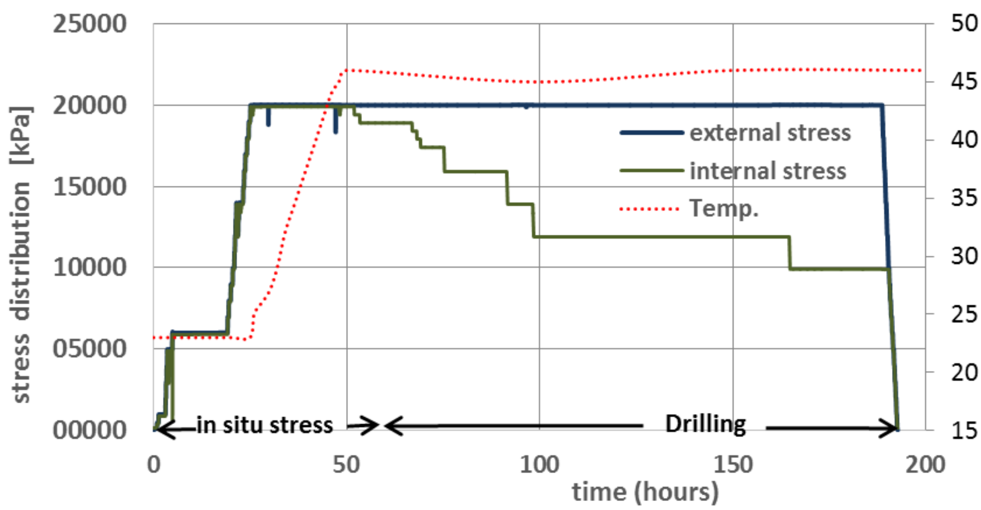
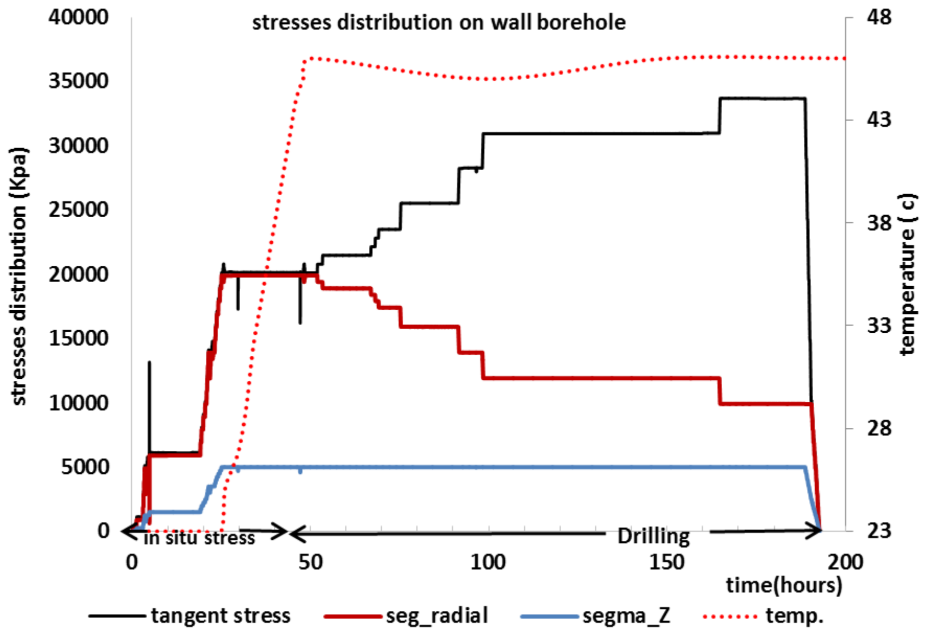


Figure 6-24 pressure distribution



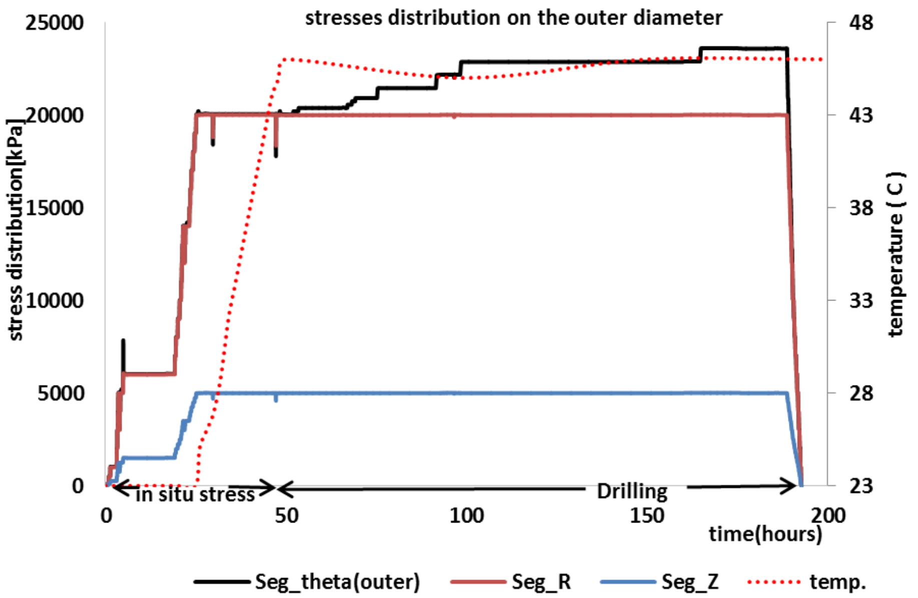


Figure 6-25 stresses distributions on the outer diameter of specimen

The test has done as planned, the apparatus has been tested for considerable period because this test has extended for more than (192 hours), its good period to extract the creep deformation during two stages in situ, and drilling. The main results have shown in the figure (6-26). The in situ stage has extended for (50 hours), and through this stage the rock salt has shown compression in axial direction by (0.5 mm) and very small expansion in borehole by (0.05mm)

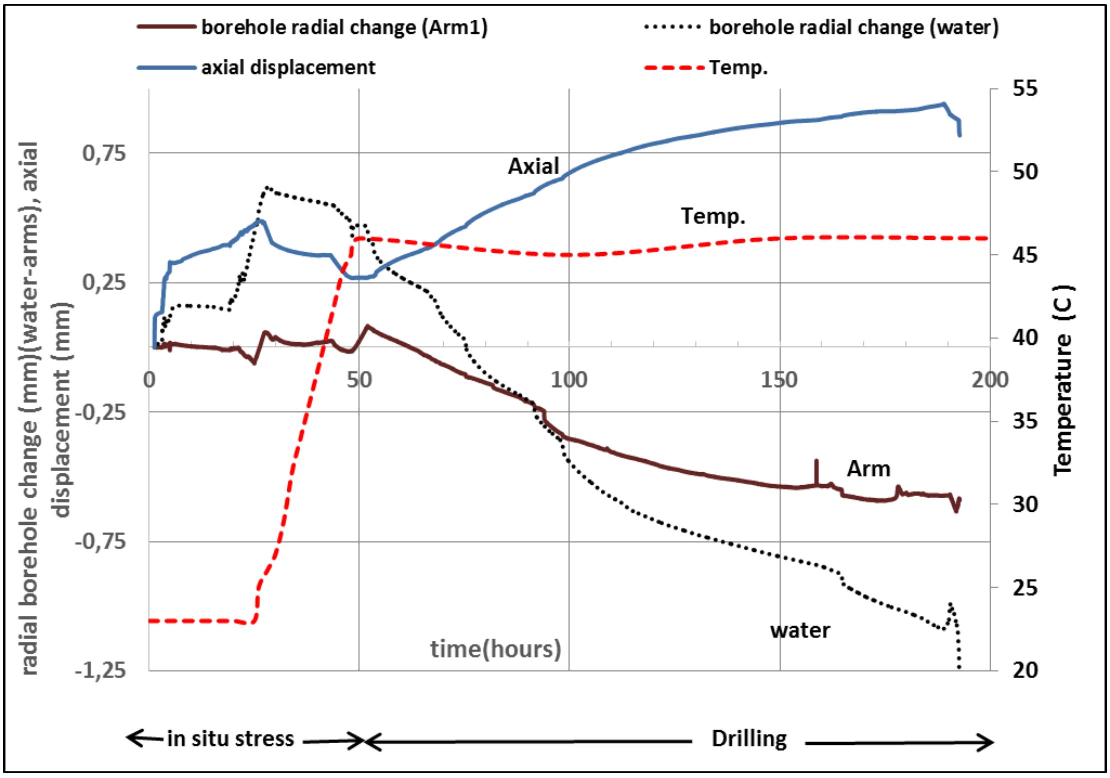


Figure 6-26 Complete test results (axial displacements, borehole deformation based both (arm &water), and temperature vs. time)

Then, the rock salt specimen has responded for heating processing (46 C), under in situ conditions by elongation of axial displacement (0.25mm), while the borehole has shown small expanding by (0.05mm). The drilling stage has extended for more (142 hours), passed through devaitoric parts (1.5, 2.5, 6, 8, and 10 Mpa), here the rock salt has experienced the same Iraqi rock salt through drilling operations. The apparatus with all internal measurement's tools and water volume increments have shown reasonable results, despite there are some difference between them, in specify the in situ stage , and the last three steps of drilling stage. The borehole has decreased at every devaitoric steps till the maximum value (0.57 mm), and axial displacement has decreased too till the final step by (0.9 mm).

Also, It has done during the tests many cycles for unloading and loading, one at (22) C and other at (45) C to check the data extracted from this test by using the internal tool and compare with standard experiment data, for instance the bulk modulus that extracted here (7.8 Gpa). See figure (6-27).

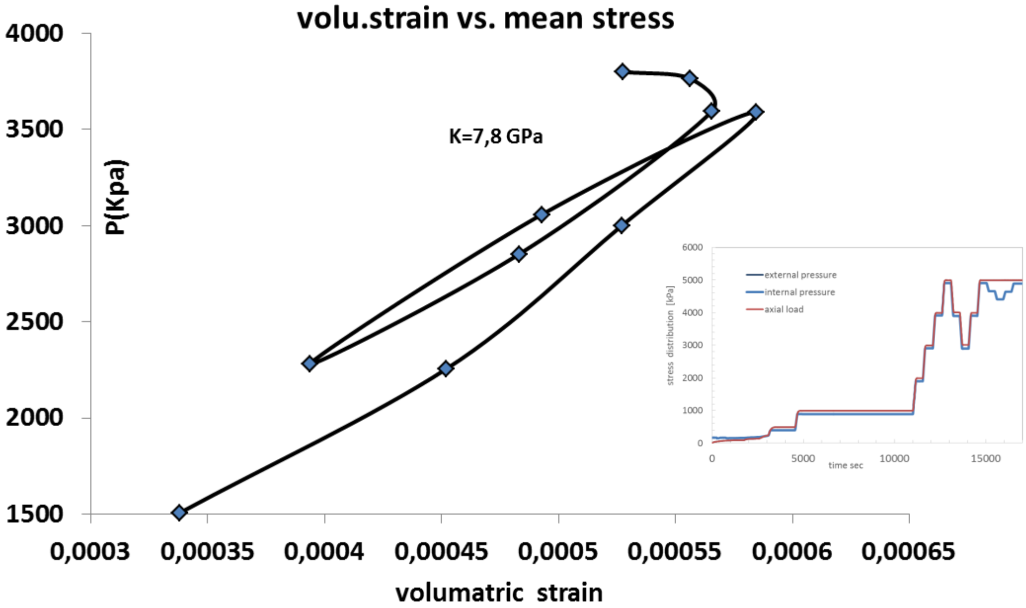


Figure 6-27 mean stresses vs. volumetric strain for unloading-loading cycle

The other data that extracted from this test are the change in outside diameter, by using external tool. However, the general trend has clearly shown the diametrical behavior of the rock salt along time of this test, but this trend has not stable, so it has been made some improvements to this tool. This new external tool has used successfully in the second test of rock salt. So, the rock salt has shown reduction during the in situ stage by (0.1mm), and when heated the rock salt has shown small expansion, as well this expansion has been through drilling stage till reach to the end of test by (0.69 mm). See figure (6-28)

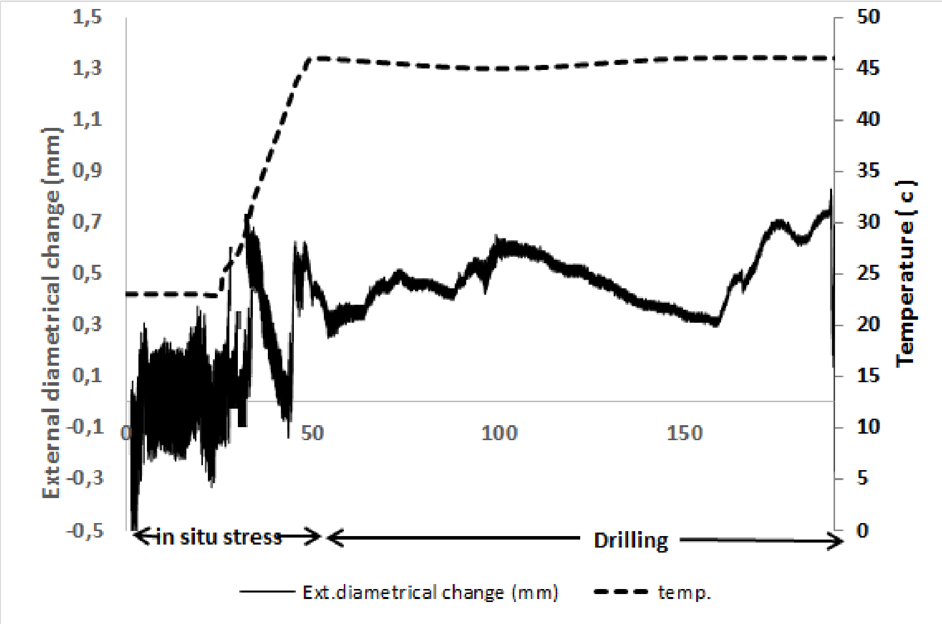


Figure 6-28 compare between axial and radial strain for the test P.1801

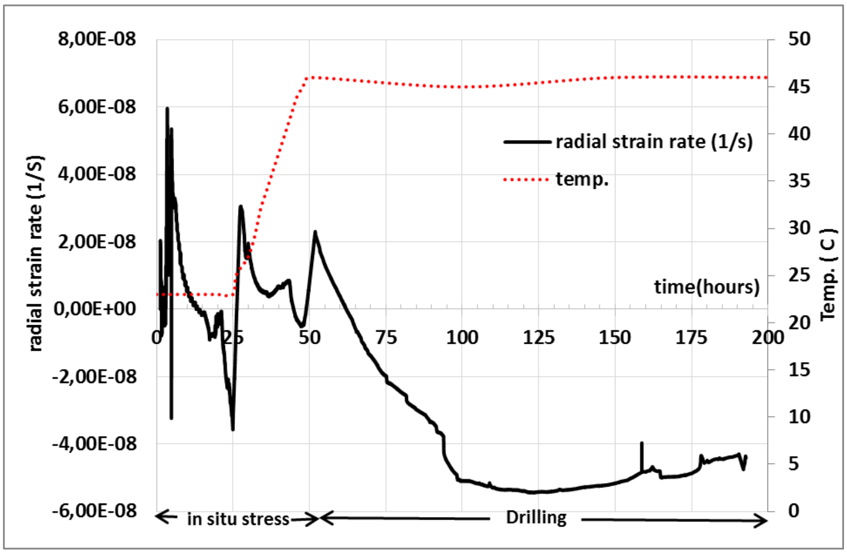


Figure 6-29 changing radial strain extracted from volume changed and one arm of internal measurement tool

The other important results of this test, are strain rate axially and internally of borehole. The strain rate at the beginning test has recorded high deformation rate ($2.5x10^{-5}$ 1/s), despite the low value of hydrostatic stress (1 Mpa), but it has been decreased steeply, till reached deformation rate ($6x10^{-8}$ 1/s) inside bore hole at the first one hour, then the strain rate has been followed the stresses changing during the test, and finally, during the drilling stage ,it has been responded for every stress steps, showing transient deformation rate through the first steps, till the step (8 Mpa), the deformation rate to steady state by ($5.4x10^{-8}$ 1/S), and started gradually increasing till , the last step (10 Mpa), the strain rate has recorded ($4.4x10^{-8}$ 1/s). See figure (6-29)

It can be followed the strain rate but in axial direction, generally ,the transient deformation rate ($2.3x10^{-7}$ 1/s) has shown during the in situ stage and smoothly decreased till ($1.6x10^{-8}$ 1/s) till the end of this stage, which has reached to the steady state creep , and keep on around this value till the end of test. See figure (6-30).

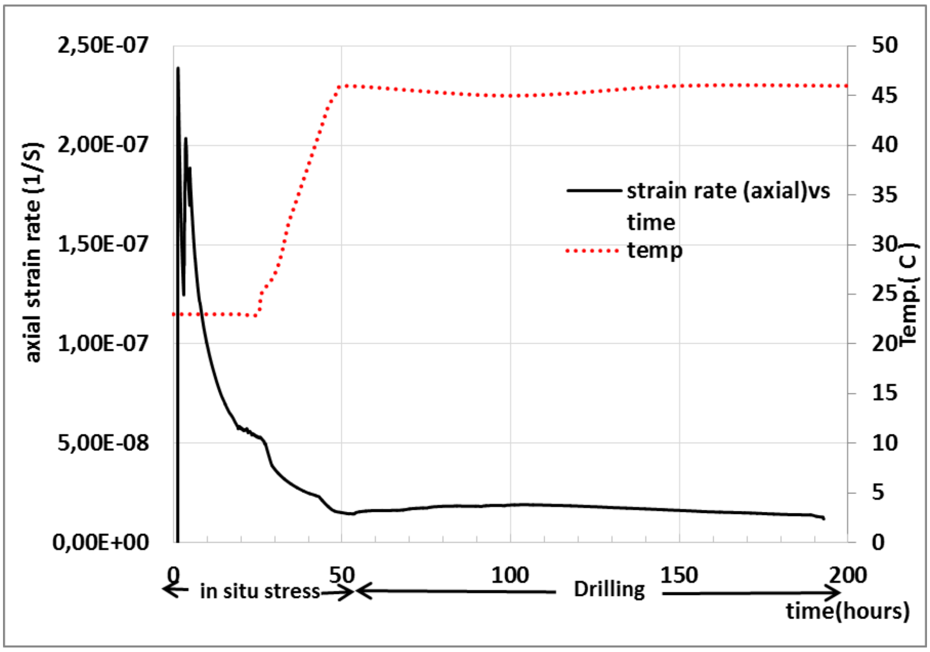


Figure 6-30 deformation rate inside the borehole of Italian rock salt

In brief, the test has covered the required data; in specify, reaching to the in situ stage without any problem(20 Mpa, 46 C), and getting all creep data during the drilling stage however the external local measurements tool need some improvements to get smooth data.

6.4.2. Second test.: HC_IT_RS#2

It has been done second test for Italian rock salt using Hollow cylinder equipment's, but with additional accessories. These accessories have included the last improvements for external measurement tool.

The test has used Italian rock salt, by applying in situ condition stage. The real in situ conditions should be applied, are (54 Mpa), but the maximum value that can be reached in the laboratory equipment's, is (30Mpa). This value is equal to (1300 Meter) with temperature (50C), while the (55 Mpa) is equal to (2350 meter) with (68C), then drilling stage which has represented by two deviatroic steps (5 Mpa and 10 Map), finally creep stage which has simulated the deformation of rock salt by measurement the closure of borehole of rock salt during three devaitoric steps (15 Mpa, 20 Mpa, and 25 Mpa).

It has been used the Italian hollow cylinder rock salt to represent the Iraq case study, and it has followed the same steps which has been done in the first test, after in situ conditions is reached , the system has been heated using three heating belts, and the heating temperature controlling by regulator. Furthermore, the shrinkage membrane has used, which support the concentric system by keeping the upper and lower pedestals' to be with the same vertical line of hollow cylinder specimen.

The pressure distributions as well the principal stresses around borehole that have established for three stages can be seen in the figure (6-31).

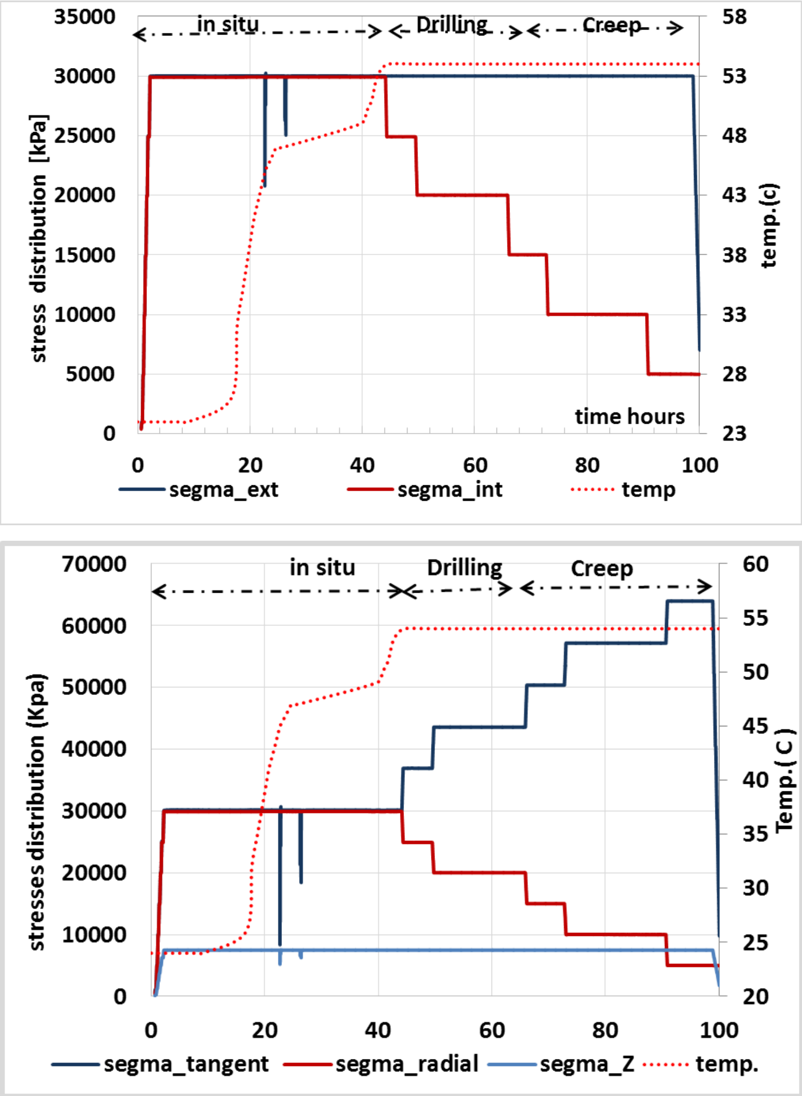


Figure 6-31 pressures distribution, principle stresses in the borehole

The figure has shown, the in situ stage has extended for more than 40 hours, , then the deviatoric stresses has begun in the first steps to mimic drilling for borehole and extended for (20 hours), and finally the creep stage that covered more than (60 hours) .It has used internal measurement tool (four arms), to measure the deformations inside borehole of hollow cylinder, in addition thermocouple cable to measure the temperature. The calibration for each arm in the internal measurements' tool has done before and after the test.

The opposite arms was elected, to show the deformations on both side of the borehole of hollow cylinder, and the results are good which have shown deformation reached to 12.8% , while the first part of the test has shown small expansion, in addition, the last three steps have shown viscos behaviour. See figure (6-32).

The both measured deformations based on water volume changed and arms , has shown coincide in the trend, (4.5 mm) is the maximum radial borehole closure deformation that recorded by water, while (2.45mm) is the maximum radial borehole closure deformation recorded by arms, and the actual borehole closure deformation was measured in the middle part of the specimen (2.43 mm). The specimen has shown compaction in all direction during in situ stress,(0.25 mm) shortening in axial direction, expansion of the borehole by (0.2 mm), and (0.6 mm) reduction of external diameter through the first (20 hours). The temperature effect has not been clear for the specimen in borehole and outside directions however, this effect is clearly shown extending at the length by (0.25 mm). The second step when the rock salt has been exposed to the same drilling operation, which represented here by decreasing the internal stress by (5 Mpa, and 10 Mpa), the rock salt shortening in axial displacement by (0.85 mm), while the external diameter expanded by (0.4 mm), and the borehole closure by (0.2mm). The last part from this test has been simulated the creeping behaviour of rock salt through three stages, also by decreasing the internal stress into (15 Mpa, 20 Mpa, and 25 Mpa).The axial and diametrical displacements have been responded with the same way of the drilling processing part, and the borehole closure has shown dramatically changing reach to (2.45 mm), while the maximum value for borehole closure based on water has reached to (4.65 mm), this difference based on the compressibility of other materials. The actual borehole closure has measured in the middle of the borehole (2.85mm), furthermore, the maximum axial displacement has recorded (1.78 mm), while the actual is (1.9mm), and finally the actual measured diameter change after the test is (0.745), while it has recorded (0.78 mm). See figure (6-33), (6-34).

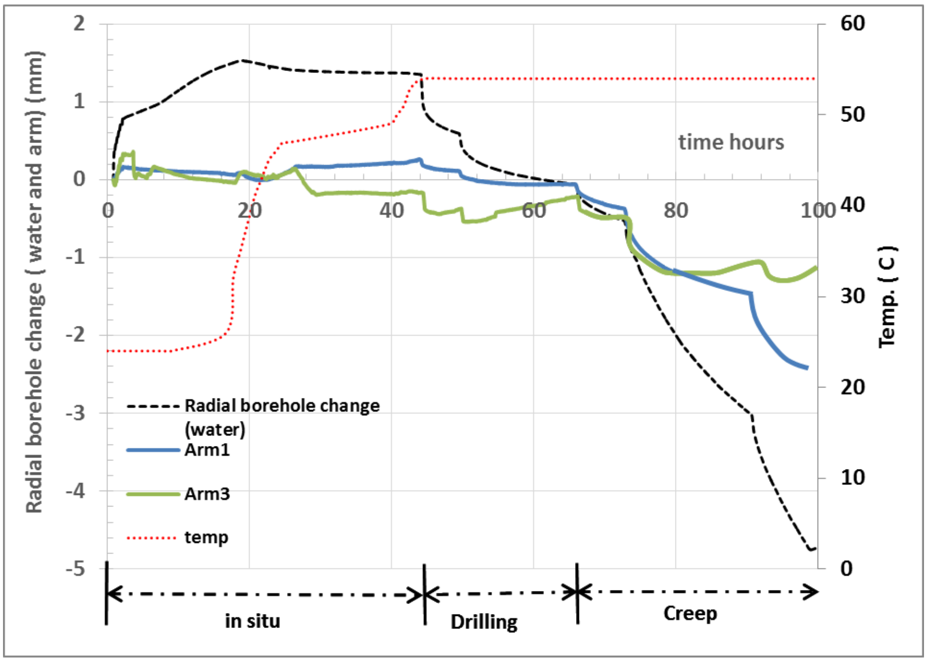


Figure 6-32 radial strain vs. time based on internal measurements' tool

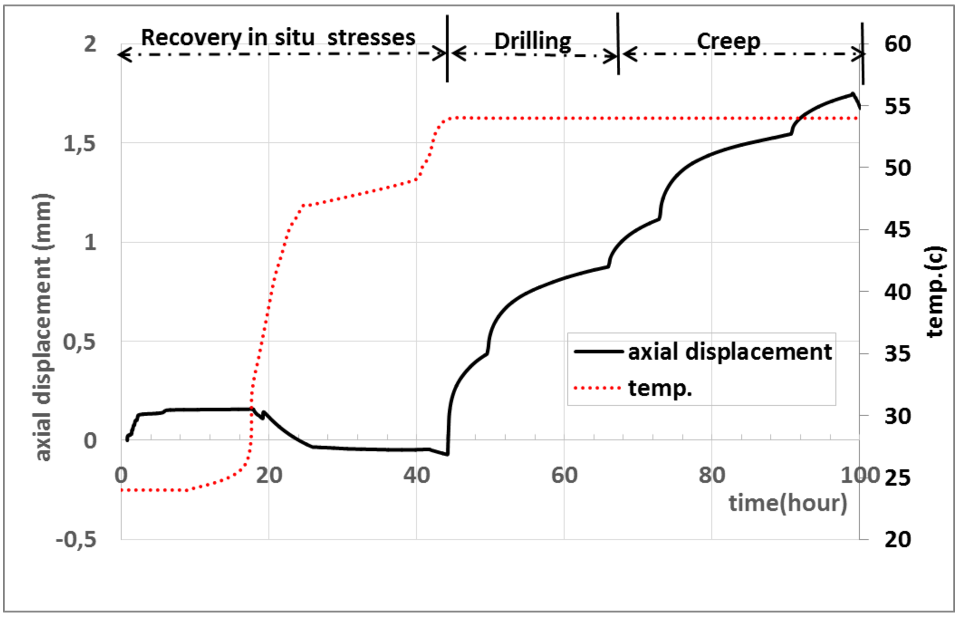


Figure 6-33 Axial displacement vs. time

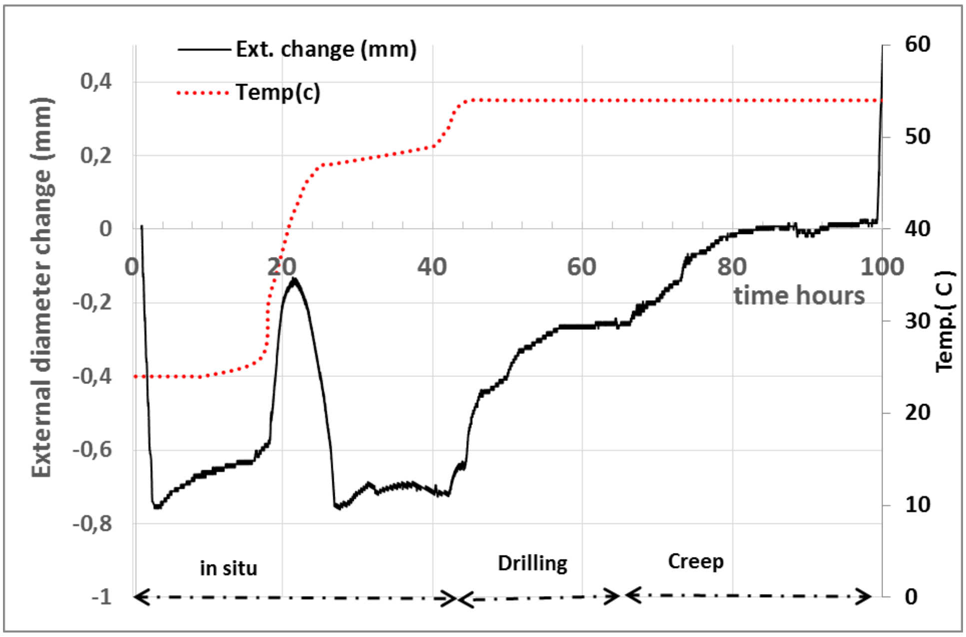


Figure 6-34 Diametrical change (mm) vs. time.

The other important data that can extract from this test, is the strain rate, to investigate when the steady state strain rate start for the Italian rock salt during the bench scale experiment. See figure (6-35). It can be seen clearly that the Italian rock salt has shown transient creep state during the in situ state conditions, starting with (1.16x10-6) and reached to ($1.35x10^{-8}$) at the first stage of heating, then it has responded when temperature changes till this temperature has remained stable at (54 C), but the Italian rock salt has entered to the steady state at temperature (48C) with value ($7.5x10^{-8}$), and it has been in this state till the end of the test ,however it has shown short period of transient deformation and quickly returned to the steady state at every stress step during the two stages(drilling, creep).

On the other hand, it can discover the behaviour of axial strain rate, which has shown in the figure (6-37). The Italian rock salt has shown transient creep rate ($1.6\ x10^{-7}$ 1/s) till (26) hours, when the steady state creep was started by rate (-$4x10^{-9}$). The figure has shown also, the transient creep state do not affected too much with temperature changes. The axial strain rate has shown increasing clearly at every step of two stages (drilling, creep), till ($4.9\ x10^{-8}$ 1/s)

In conclusion, the test has given the good results and covers all stages of the Iraqi case study, and approved the ability this apparatus and all measurement tools.

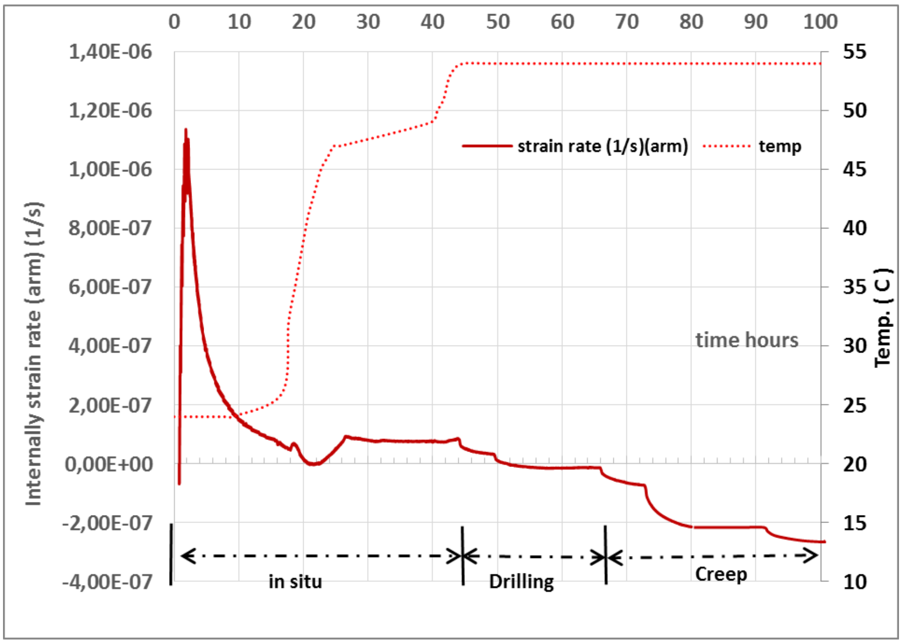


Figure 6-35 radial strain rate (1/s) vs. time

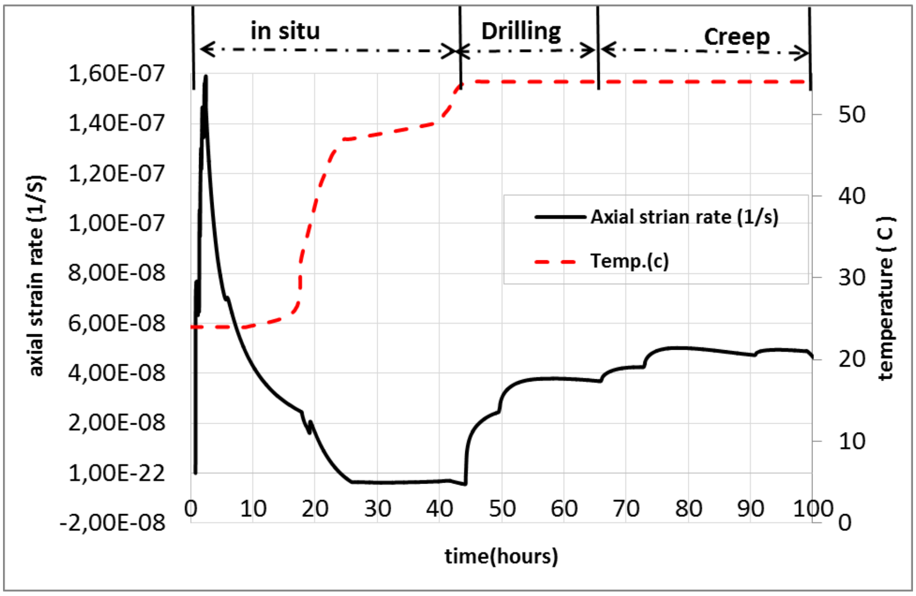


Figure 6-36 axial strain creep rate vs. time

Chapter 7: Theoretical and empirical laws : from experiments to the case studies simulation

7.1. Introduction

The most of models in chapter (2), have been reviewed, that have been using to analysis and study different engineering structural as repositories for store strategically material and boreholes of oil and gas wells. Choosing models actually depends on the targets and the engineering structural, for instance the models that have been using to study borehole stability in oil wells, are linear elastic or liner viscoelastic because these models have been given acceptable results, and covered the engineering problem.

furthermore, the elastic model will be enough to predict (Dusseault et al,.2004), also, the Maxwell rheological model has been used to predication the closure of the borehole , however some engineering structural projects demand complex model which can describe long term creep of rock salt, these models have been taken account tertiary stage which including damage and ruptures (Wang et al 2014)

On the other hand, a UCS test was used to predicate viscous behaviour as well elastic part (Singh et al,.2017), by using Maxwell model to predicate the viscous behaviour from different strain rate on UCS.

The exponential stain curve derived from the Kelvin rheological body was adopted to reflect the transient creep which, was based on Carter power law. The Norton law with two parameters was used here also.

It has been shown here, that generalised Hock Brown failure criterion giving good results compare with other two criteria Mohr Colombo and Durker purger. Furthermore, it has been determined experimentally the dilation boundary for the Italian rock salt as well compare with Spires criterion and Ratigon.

7.2. Applying failure criteria for analysis

Through previous chapter it has shown, analysis for both Mohr Colombo and Hock Brown criteria. The experimental data that are extracted, should be studied in order to get at least the failure envelop and dilitancy boundary to compare between the Italian rock salt and Iraqi salt, because some Iraqi rock salt case studies have been depended on the parameters of the Italian rock salt, then the predication will be compromised if the behaviours of both rock salt will be the same.

7.2.1. Mohr-Coulomb criterion

Most of articles are agreed that the Mohr-Coulomb, are the widely used failure criterion for soils and rocks, which is based on the shear failure that will be happened at any plane reaches. The relation can be defined in shear and normal stresses as:

$$\boldsymbol{\tau_m = c + \sigma_n \tan\varphi} \text{ ....(7-1)}$$

The two parameters that connect the relation between shear (σ_n) and normal (τ_m) stresses, are the internal friction angle (ϕ) and cohesion (c). It can be expressed by the two principles stresses, while the intermediate stress was neglected here.

$$\boldsymbol{\sigma_1 = \frac{1 + \sin\varphi}{1 - \sin\varphi} * \sigma_3 + \frac{2c * \cos\varphi}{1 - \sin\varphi}} \dots\dots\dots (\mathbf{7-2})$$

The MC criterion reduces to Tresca criterion when internal friction angle will be zero, and both equations (1), (2) have been shown straight lines in the spaces of (p-q),(σ_1-σ_3) and(τ-σ_n). See figure (7-1).

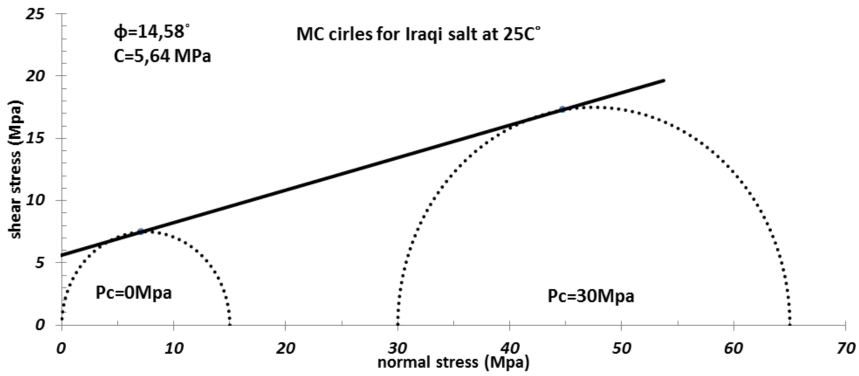


Figure 7-1 MC circles for Iraqi rock salt

7.2.2. Durker Purger criterion

This criterion is applied sometime in rock mechanics, the general form for this criterion as follow:

$$\mathbf{J_2^{1/2} = \alpha I_1 + k} \ldots\ldots\ldots \textbf{(7-3)}$$

The working space of this criterion represent by the first invariant of stress ($I_1=\sigma_1+\sigma_2+\sigma_3$) and the second invariant deviatoric stress ($J_2= [(\sigma_1 - \sigma_2)^2+ (\sigma_2-\sigma_2)^2+ (\sigma_3-\sigma_1)^2]/6$). The two fitting parameters(α),(k) which depends on the rock materials, can be obtained from the slop and intercept of line into the space between ($J_2^{1/2}$) and (I_1), this criterion convert also to Von Mises criterion, when (α) equal to zero.

The two parameters also can be obtained from the values of unconfined compressive strength and tensile strength as follow:

$$\mathbf{C_o = \frac{\sqrt{3} * k}{1 - \sqrt{3}}} \ldots\ldots\ldots\ldots\ldots (\mathbf{7-4})$$

$$\mathbf{T_o = \frac{\sqrt{3} * k}{1 + \sqrt{3} * \alpha}} \ldots\ldots\ldots\ldots (\mathbf{7-5})$$

The space for this criterion is linearly in both (p-q) and (σ_1-σ_3), and for tri axial test the equation will be:

$$\boldsymbol{\sigma_1 = \frac{1 + 2\sqrt{3}\alpha}{1 - \sqrt{3}\alpha}\sigma_3 + \frac{\sqrt{3}k}{1 - \sqrt{3}\alpha}} \ldots\ldots\ldots. (\mathbf{7-6})$$

7.2.3. Hoek-Brownn criterion

It is considered empirical non- linear relationship that was created by Hoek .The Hoek Brown criterion is covered a wide range of tri-axial test data, the criterion connect the major and minor principles stresses by the following equation:

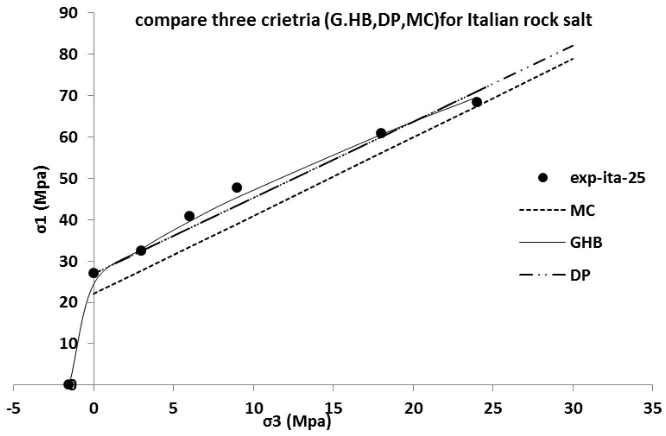
$$\boldsymbol{\sigma_1 = \sigma_3 + \sigma_c * \sqrt{m * \frac{\sigma_3}{\sigma_c} + s}} \ldots\ldots\ldots.(\mathbf{7-7})$$

The two parameters here, (*m*) and (*s*) are dimensionless which related to characteristics of rocks; (m) reflects the degree of hardness and (s) represent the disturbance grade ranged (0-1). It was improved this criterion by Hoek into general form by using uniaxial compression strength of the intact rock, as well the two dimensionless parameter's (*mb*), (*s*).and add the other parameter (a).

$$\boldsymbol{\sigma_1 = \sigma_3 + \sigma_{ci} * \left(mb * \frac{\sigma_3}{\sigma_{ci}} + s\right)^a} \ldots\ldots\ldots(\mathbf{7-8})$$

This is generalized Hoek Brown form. So after this small introduction, three criteria were used here to get comparison for failure envelopes for both Italian and Iraqi rock salts.(Ma et al,.2013).

It has been applied these criteria and compare with experimental data. See figure (7-2).



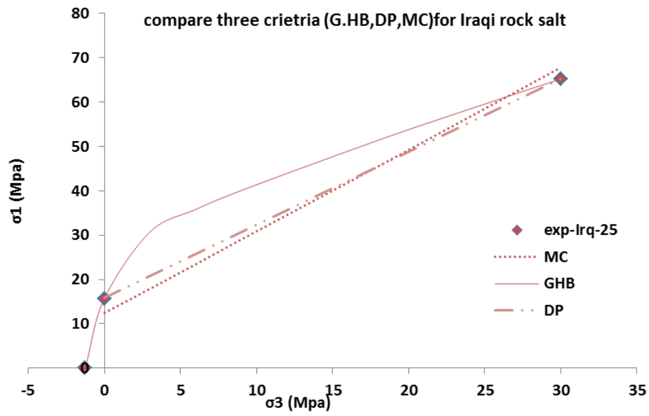
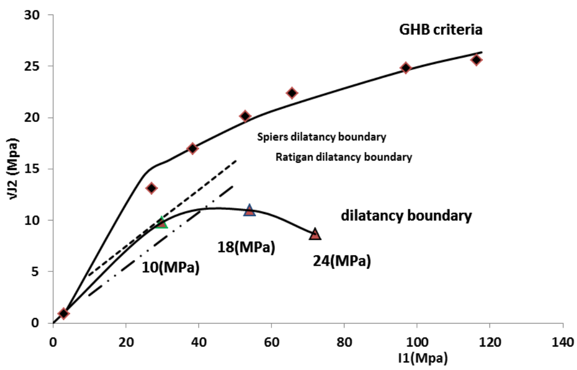


Figure 7-2 three failure criteria for Italian &Iraqi rock salt.

Both rock salt have been shown that (GHB) are more compatible with experiments data, while (MC) has shown underestimated for less confining pressure, but shown over estimated at high confining pressure , even with some difference in this value of confining pressure for two types of rocks. The (DP) criteria has shown for Italian rock salt close to the (GHB) however the relationship is linearity, on the other hand, for Iraqi salts the criteria is very close of (MC).

For complete description of the Italian rock salt, it can be used the experimental data for constant mean stresses tests to extract the dilatancy with damage factor. See figure (7-3)



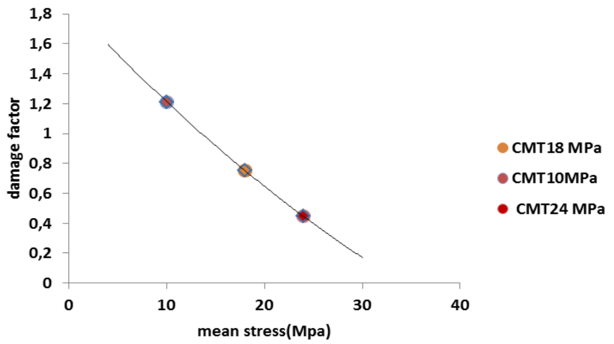


Figure 7-3 (GHB) envelope failure and dilatancy boundary (upper).damage factor for three (CMT) of Italian rock salt

Its clearly, at high mean stresses value the rock salt has been shown less tending to dilatate , while at less mean stress , more damage was created , it has been shown by damage factor value curve. This trend is compatible with two diltancy cretiera(Ratigan, Spires).

7.3. Applying Norton power law .

The creep strain rate is very important properties in the creep test, because it can be fitted the flow law of the rock salt, then through this flow law, can be predicted the closure of borehole front of rock salt. This general flow law is companied with the Von Mises stress; this power flow law takes a form:

$$\acute{\varepsilon} = \mathbf{A} * \boldsymbol{\sigma}^{\mathbf{n}} \quad \text{.......................... (7-8)}$$

A, is a material constant [Pa^{-n} s^{-1}].

σ, is Von Mises stress [Pa].

n, is a dimensionless material constant.

It can be obtained (A), and (n) by taking natural logarithm for both sides of the equation:

$$\ln \acute{\varepsilon} = \boldsymbol{n} * \ln \boldsymbol{\sigma} + \ln \boldsymbol{A} \quad \text{................ (7-9)}$$

Through this linear equation , it can be fitted by plotting measured value of strain rate and Von Mises using simple linear regression which can obtained (n) , and (A) in (lnἑ) –(lnσ) space.

This procedure results in a purely empirical fit to describe flow behaviour. however it should not be interpreted in terms of any specify mechanism of flow, because this method was assumed one mechanism of flow operates (steady state creep), while if it will be assumed multiple mechanisms of flow many general be active (Urai et al,.2008) (Van Keken et al,.1993).

furthermore to examine our experiment data more, it was plotted these results on a map which was created by collected data experiments for low temperature of a wide range of rock salts which extended on different laboratories (Sandia ,BGR ,Utrecht University and other laboratories)(see figure(7-4) (Urai et al,.2007).solid line for room temperature solution –precipitation creep law of different grain sizes, while the broken line is extrapolating of the (grain size insensitive) dislocation creep law(n=5), it’s clear both Italian and Iraqi experimental data has been taken position near to dislocation creep , as well the small grain size of Iraqi rock salt has been shown tending to fast creep (less than 120 days),which was happened in high differential stress (20 -30) MPa, also for Italian salt, while the big grains for Iraqi salt ,and when the differential stresses are less than (10)MPa, the Iraqi rock salt tend to creep because pressure solution processing..

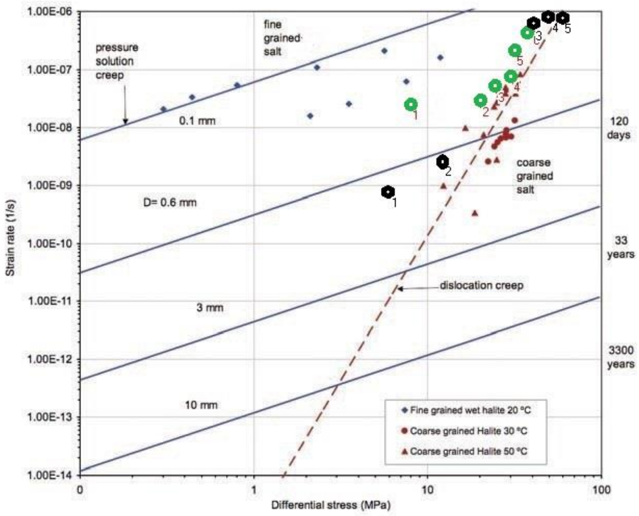


Figure 7-4 Figure (7-1)Italian and Iraqi experimental data compare with other worldwide collects experimental data(Urai et al,.2007) (Iraqi salt black dot, Italian salt green dot)

After that, it has been known, it might be the empirical flow that was designed for one mechanic process, apply in our creep tests. It has been plotted Von Mises stresses vs. strain rate to extracted the two parameters (n), and (A). See figure (7-5), and table (2).

Temperature (C)	Dimensionless Parameter (n)	Material parameters(A)
25	3.78	3.955×10^{-35}
66	2.6322	6.167×10^{-26}

Table 2 (n),(A) parameters in two temperature

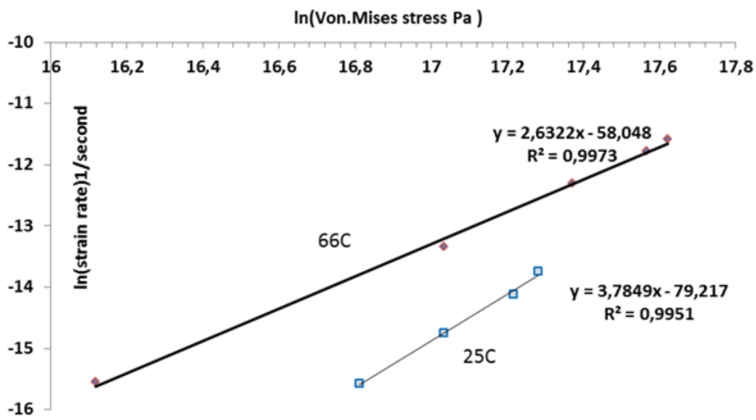


Figure 7-5 Von Mises stresses vs. Strain rate for two creep tests with different temperatures (25C, 66C).

Creep testing on the Italian rock salt show that the Norton flow law, provides an adequate fit to observed creep behaviour on one step (28Mpa) at (25C) ,while the lower this deviator value, the results are under estimated ,on the other hand, at deviator step more than (28 Mpa), the result are overestimated .

The same story has been observed for creep test under (60C), but here the good fitting at deviator (30MPa). See figure (7-6)

Generally, it can be considered good results because both of tests were done in multistage creep tests, and the period of all tests, were not more 8 hours. So it was not enough time to reach for steady state even the trend seemingly was stable .

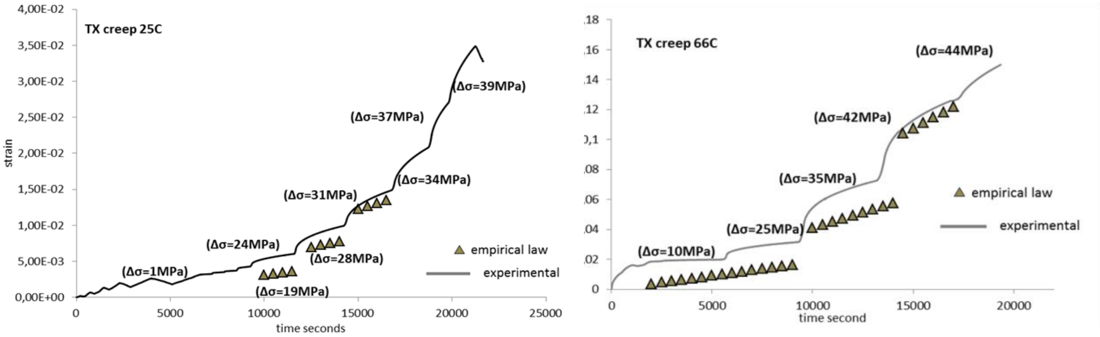


Figure 7-6 comparison between empirical law creep and experimental for 25C and 66C

7.3.1. Other example for applying Norton power law.

The previous test was done under fixed axial stress and reducing confining pressure to simulate excavation processing under constant deviatoric stress using Hoek cell apparatus.

Here, it has applied Norton power law for some advanced creep test, where the rock salt has loaded by fixed confining pressure and changed the axial loads for every loaded stage. Actually the test has done for both Italian rock salt and Iraqi rock salt under room temperature, but the results have been gotten for just Italian rock salt because it has reached for steady state through period of the test.

Three steps have done, but the rock salt has failed into third one, so, two points for steady state have got, then plotted in $(\ln q)$ - $\ln(\acute{\varepsilon})$.

See figure (7-7)

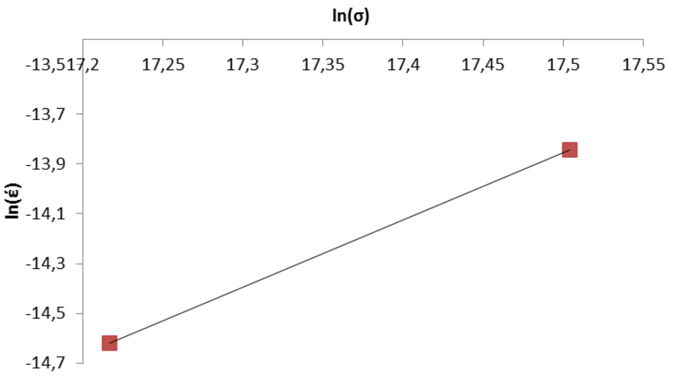


Figure 7-7 space for natural logarithmic deviatoric stress and strain rate for Italian rock salt creep test

It was extracted the two parameters for power law fitting (n=2.692) and ($A=3.21*10^{-27}$ s^{-1}), to see how much this power law compatible with experimental data. It has plotted both experimental and modeled data by using Norton power law for steady state condition. See figure (7-8).

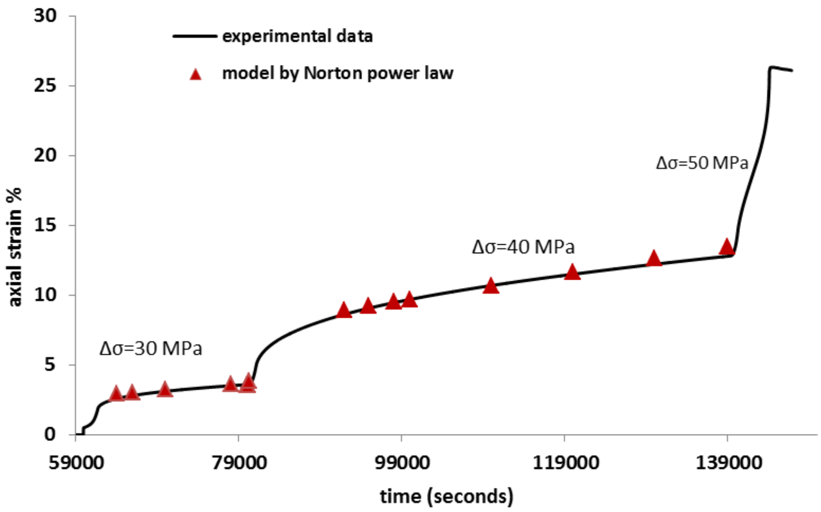


Figure 7-8 comparison between experimental data with Norton power law data.

7.3.2. Applying Norton power law for Iraqi rock salt

In order to know that power law can be applied for Iraqi rock salt, as it has done for Italian rock salt, the same procedure has been done for Iraqi rock. It has collected all steady strain rates that has obtained from the experiments, it has just three points where the steady state creep achieved, because the time that has spent for every first load has no longer enough to get steady state. It has plotted these points in natural logarithms of strain rate and von Mises stresses. See figure (7-9).

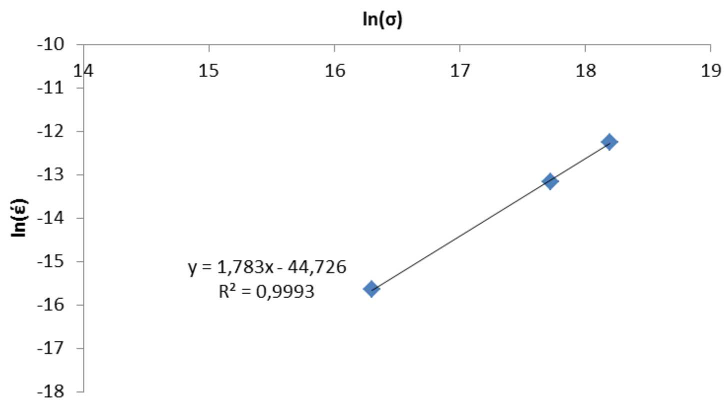


Figure 7-9 space for natural logarithmic deviatoric stress and strain rate for Iraqi rock salt creep test

It has extracted the parameters for Norton power law (n=1.783) and ($A=3.76*10^{-20}\ P^{-1.783}\ .s$), when applied Norton flaw law on Iraqi rock salt, the correlation is not good. See figure (7-10).

In contrast with the Italian rock salt, the Norton power law is given good results while Iraq rock salt, for loaded (40Mpa), it is underestimated, overestimated for loaded (60Mpa), and moderated for (50Mpa).

The reason is the less data that has extracted from experiments because a few raw materials and the Iraqi rock salt need long term creep test to reach for steady state.

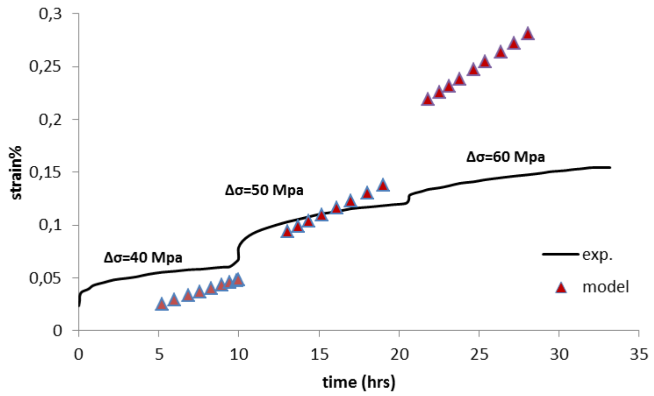


Figure 7-10 comparison between modeling by power law and experimental data for Iraq rock salt.

7.3.3. Norton power law for case study

It should look for the case study in order to check the experimental parameters for empirical creep law. Fortunately, the well no.15 (case study), It had been run the calliper log to measure the changing in borehole front of rock salt for different periods in open borehole without any casing pipes. The history of borehole changing and deviatoric stresses front the rock salt (less than 4 meter) can be seen in the figure (7-11).

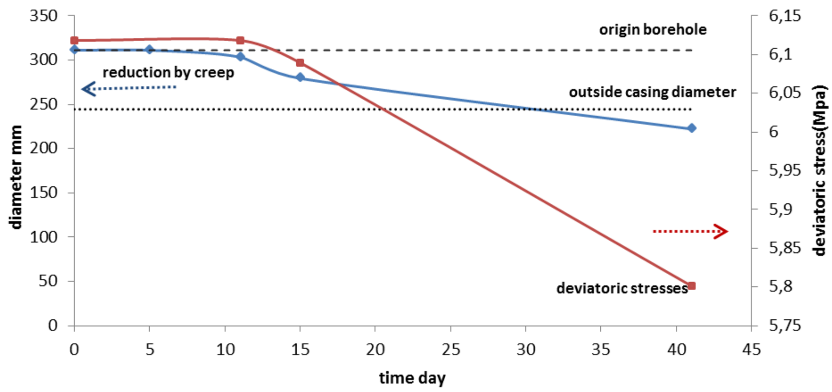


Figure 7-11 borehole closure and deviatoric stresses history of well.no.15

Through this well, the rock salt had been loaded the casing later when the well was ready for completion processing, then all completion operation had been postponing because the casing was collapsed, and that was clearly happened after 32days.

So, in order to check that through empirical creep law, it has applied this predicated law at the same depths and of rock salt which had been crept, despite the temperature of this well (80C) is higher than of the experiments tests (66) because the depth of this rock salt bed is (2939 meter). See figure (7-12).

The results are reasonable, because the trend of real borehole closure has been very close to predicated borehole closure by empirical creep law (66C). The difference between them has just 12 days when the collapsed the casing, the reason behind that are due to the temperature difference.

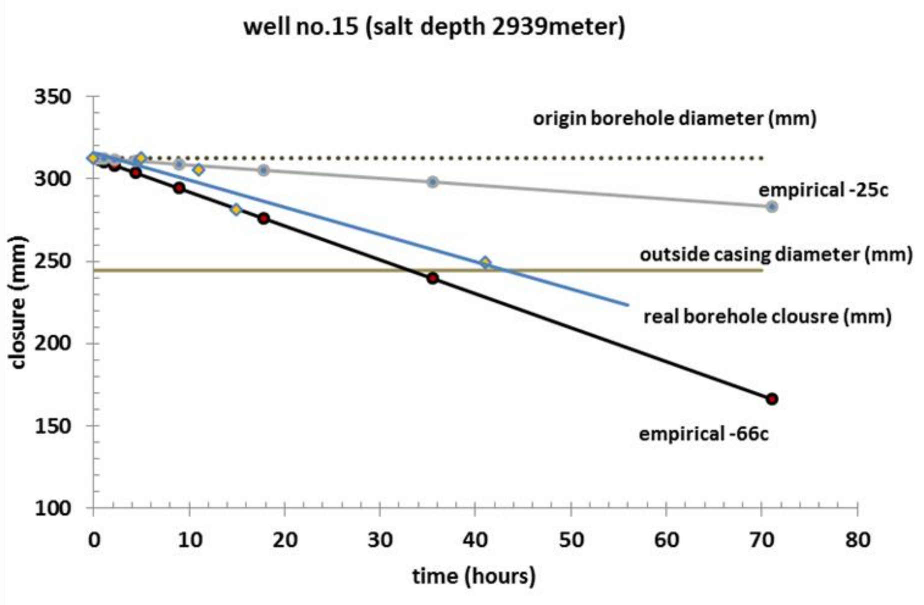


Figure 7-12 predicated and real borehole closure of well no.15

On the other hand, it has applied the Norton power law with parameters that have extracted from some short term creep tests, for the same case study. See figure (7-13)

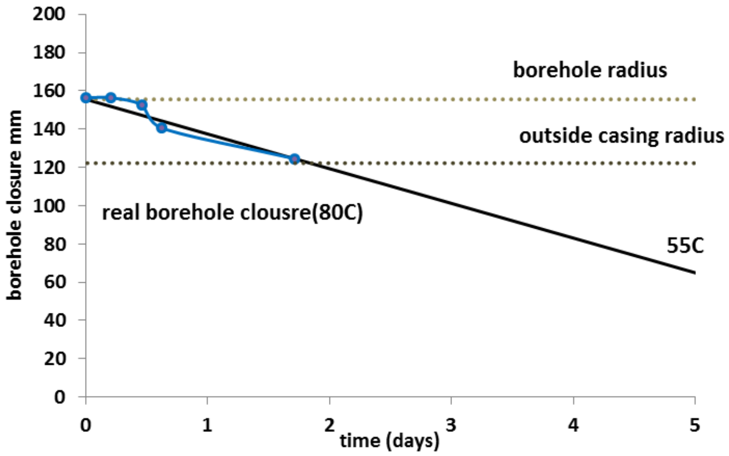


Figure 7-13 Norton power law for Iraqi case study

Seems the parameter that have extracted are reasonable, because some tested have done at (55C), and the real case study temperature is (80C), as it know, the temperature is the main player after the deviatoric stresses, for that reason, the Norton power law trend overestimated for period less than (1/2 day), while it has underestimated for period more than (1/2 day).

7.4. Double mechanics creep law (Munson et al,. 2004) from creep test results

It has collected from different tri-axial compression creep tests, these tests have done at (30Mpa) confining pressure, and under different deviatoric stresses, in order to discover the value of stress which is called reference stress that the rock salt changing its' trend because the changing the micro-mechanic processing, for instance from glide dislocation to undefined mechanics, see figure (7-14).

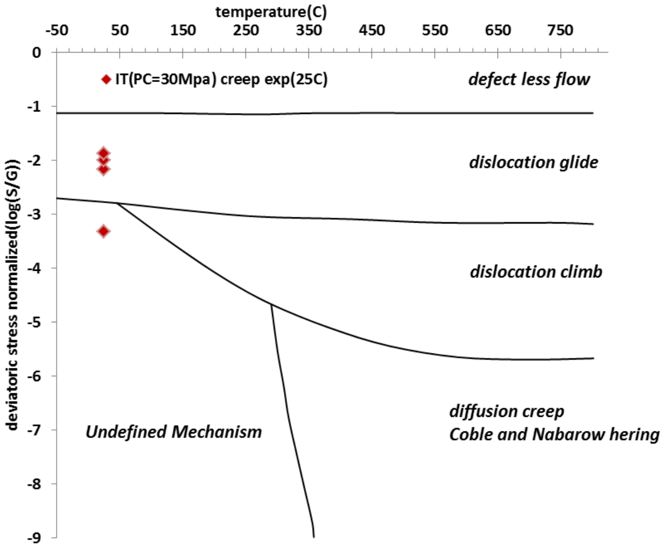


Figure 7-14 , rock salt mechanics map and Italian rock salt creep test

In another word, this point divided the behaviour for low stress and high stress. The results of these tests can be seen in table (3).

Deviatoric stress (Mpa)	Strain rate (1/S)	Temperature (C)	Confining pressure (Mpa)
1,4	5,24E-08	25	30
20	1,72E-07	25	30
30	4,50E-07	25	30
40	9,27E-07	25	30

Table 3 strain rate and devaitoric stresses for tri-axial compressive creep test

In order to get the reference stress when the steady state strain rate changing the trend due to micro-mechanic processing, it should be plotted these values .See figure (7-15).

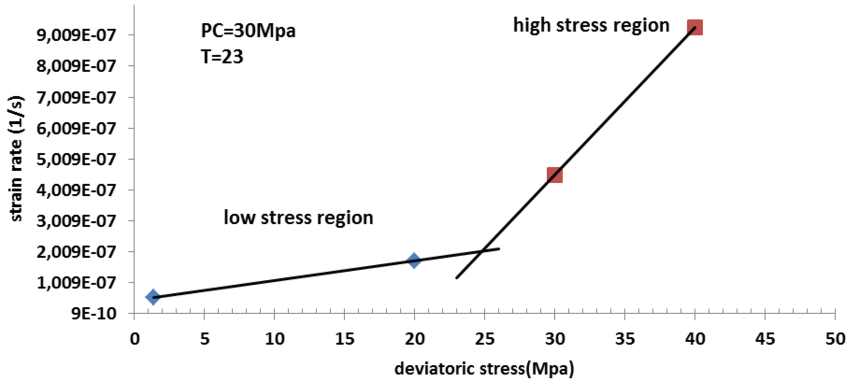


Figure 7-15 results for tri-axial creep test under confining pressure (30Mpa)

The figure has shown two regions, one for low stress and other for high stress. It can be applied Double mechanics creep law (Singh et al,.2017).

The main structure of this law which can apply just for steady state creep as follow:

$$\boldsymbol{\varepsilon_s} = \acute{\varepsilon}_{\mathbf{o}} \left(\frac{\boldsymbol{\sigma_{\mathrm{eff}}}}{\boldsymbol{\sigma_o}}\right)^{\mathbf{n}} * \mathbf{exp}\left(\frac{\mathbf{Q_o}}{\mathbf{RT_o}} - \frac{\mathbf{Q_1}}{\mathbf{RT_1}}\right) * \mathbf{t} \ldots\ldots\ldots\ldots..(\mathbf{7-10})$$

n. material parameters (**2.5122**) for high stress region.

$\mathbf{Q_1}$, $\mathbf{Q_o}$- Effective activation energy at $\mathbf{T_o}$; $\mathbf{T_1}$ **(42.4, 47) KJol.mol**$^{\mathbf{-1}}$

R - Universal gas thermo-mechanical constant.(**0.00831224 J.mol**$^{\mathbf{-1}}$**.K**$^{\mathbf{-1}}$).

$\mathbf{T_o}$; $\mathbf{T_1}$ (temperature at reference (298K), and at boundary condition (339K)

$\boldsymbol{\sigma_o}$ reference stress(extracted from experiment).

$\boldsymbol{\sigma_{\mathrm{eff}}}$ effective stress.

$\acute{\boldsymbol{\varepsilon}}_{\mathbf{o}}$ strain rate at reference condition. (**1/S**).

This creep law has applied for steady state case, and it has applied for one creep test of Italian rock salt (table 7-2), that has done at (30Mpa) confining pressure and under high stresses (30 Mpa and 40 Mpa). The result is convenes. See figure (7-16).

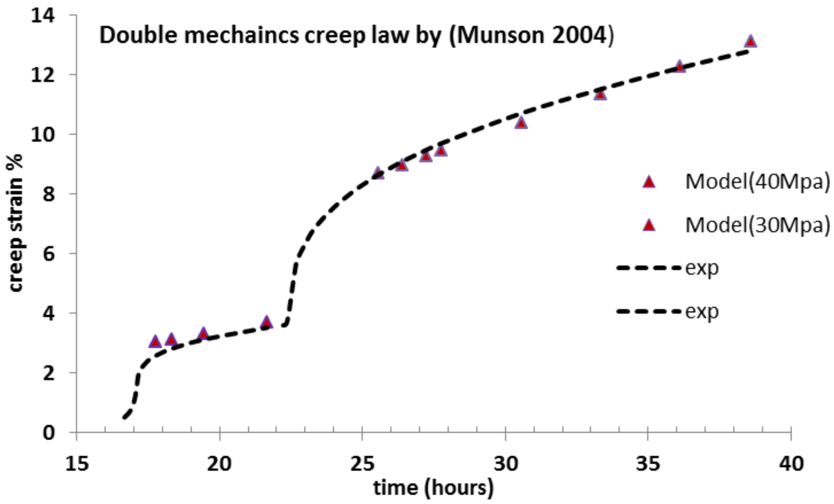


Figure 7-16 Double Mechanics model (Munson et al 2004) compared with creep experiment under (30Mpa) confining pressure.

It has used this model for one of Iraqi case study (well FQ15) and it has seen when the deviatoric stress (8Mpa), the model more convenience with real reduction of the borehole. See figure (7-17).

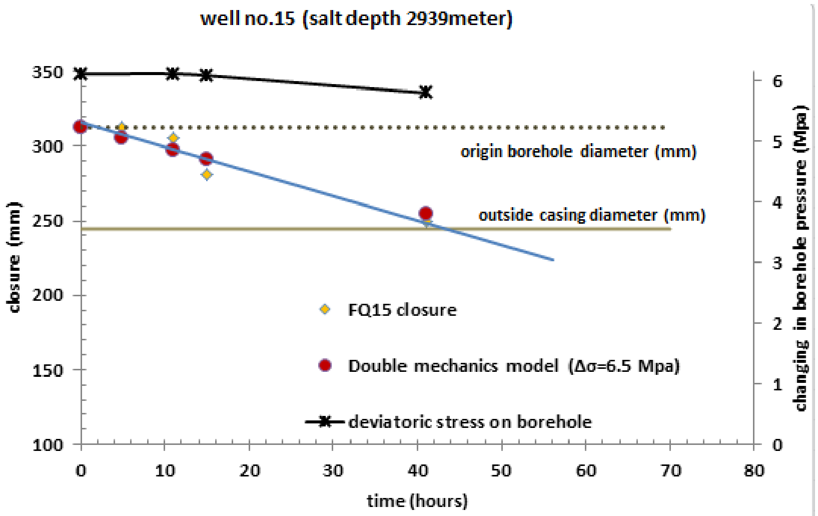


Figure 7-17), double mechanics model (Munson et al,.2004) for case study (FQ15).

7.5. Applying Carter model .

There are different models that deal with creep of rock salt, here it has adopted Carter model, and benefits from experiments that have done. This model able to estimate the creep behaviour through two states, transient and steady state , and was developed by Wang (Wang et al,.2004) to evaluate the tertiary creep by calculating the damage factor as well the state after damaged. Here, it has been elected transient and steady state laws because most the Iraqi cases studies have been worked under two these states.

The model has verified by two cases, based on the test data for WIIP salt at high stress level and low (Munson et al,.2004).

The transient creep law is

$$\boldsymbol{\varepsilon_t = \frac{\sigma}{C_1} * \left[1 - \exp\left(-\frac{G}{C_2}t\right)\right] \ldots\ldots\ldots (7-11)}$$

And for steady state creep is:

$$\boldsymbol{\varepsilon_s = A_1 * \exp\left(-\frac{Q_1}{RT}\right) * \sigma^2 * t \ldots\ldots..(7-12)}$$

The parameters were modified to be fit with experimental data.

A_1, C_1, C2, n, material parameters

Q_1- Effective activation energy

R - Universal gas thermo-mechanical constant.

T- Absolute Kelvin temperature in K

G- Shear modulus

σ- Deviatoric load

t- Time seconds

The parameters used in the model are as follows:

A_1= 3.02*10^{-2} $Mpa^{-6.023}$, (C_1= 5.65)(C_1= 1.68*10^{-1}) Mpa^{-1},(C_2= 4.64)(C_2=98.8 Gpa^{-1}),n=6.023,

Q_1= 41KJ.mol^{-1}, R=0.00831446 J.mol^{-1}, T=298 K, G=2.96 Gpa.

It has applied this model on Italian rock salt creep test. The model gives good result. See figure (7-18).

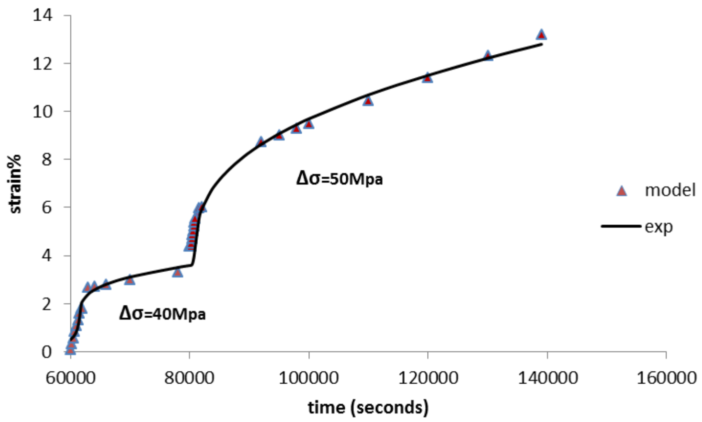


Figure 7-18 Carter model for creep test of Italian rock salt

At the same context, Carter model has applied on Iraqi rock salt creep experiment, of course the parameters have modified to be compatible with experiment condition, because this experiment has done under temperature (55C). See figure (7-19)

The parameters as follow:

A_1= 3.04*10^{-2} $Mpa^{-5.0932}$, (C1= 2.09) Mpa^{-1}, (C2= 1.41), n=5.0932,

Q_1= 41KJ.mol^{-1}, R=0.00831446 J.mol^{-1}, T=328 K, G=2.96 Gpa.

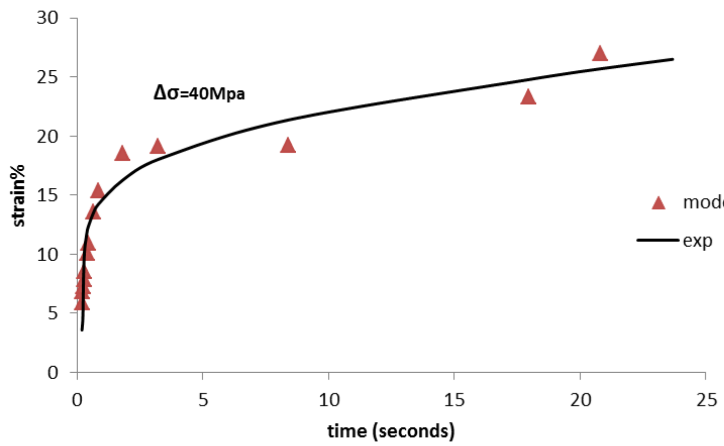


Figure 7-19 carter model for creep test under (55) C, PC=30Mpa.

7.5.1.1 Applying Carter model for real case study

After applying the Carter model for two creep experiments for Italian and Iraqi rock salt, which has given good results, it's applied this model for one of case study to evaluate the creep behaviour and then can be predicted .See figure (7-20). The figure has shown that the realistic of the Carter model to evaluate and predict the behaviour of Iraqi rock salt from engineering point of view, despite the data that available from case study had been got by the intervention processing to solve the reduction on the casing pipes rather than focus on measuring the reduction of borehole by using calliper logs for not far measure periods, because the reduction internal casing pipe diameter do not reflect directly how much the rock salt was crept. So, it can be considered that this method can evaluated as well predict.

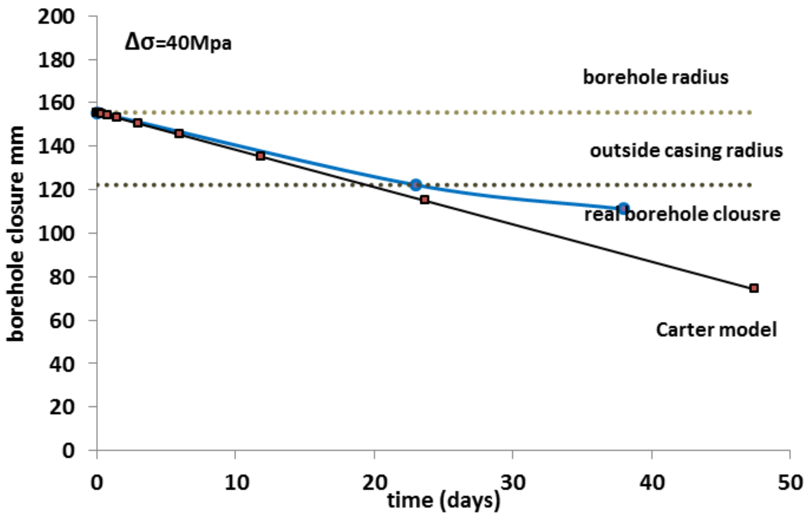


Figure 7-20 Cater model is applied for case study

However, it can be assumed, sometimes the brine fluid (sp.gr. 1.22 gm/cc) had been supported the casing by decrease the difference stresses on the rock salt from (40Mpa) to (25Mpa), despite this assumption was optimistic because most bad cementing operations leaves irregular isolated spotting without any supported. So, the rock salt had been crept in quick way to load the casing after short period compare with normal creep (0.002year^{-1}) through these spotted, as the Carter model and real creep trends has shown. On the other hand, the long section of rock salt do not effect as small thickness of inter-bedded salt with some clays, as in the Iraqi case study, the collapsed casing was happened in the section of rock salt not extended for (3 Meter),and inter-bedded with anhydrite and shale. Those impurities clays are considered as the main engine of the quick creep.

7.6. Bogobowciz for borehole closure

This method was developed by Bogobowicz (Bogobowicz et al,.1991) for steady state closure of opening in non- Newtonian viscous material as follow:

$$\mathbf{v_o = r * \frac{\sqrt{3}}{2} * \acute{\varepsilon}_o * \left(\frac{\sqrt{3}}{n} \frac{(\sigma_v - P_b)}{\sigma_o}\right)^n} \ldots\ldots\ldots (\mathbf{7-13})$$

$\mathbf{v_o}$ The borehole closure rate

n constant was assumed =**5.5**

$\acute{\varepsilon}$ calibrated strain rate coefficient **($1x10^{-8}$ s^{-1})**

The calibrated strain rate coefficient as a pivot for this equation, can be approximated for nearest dry salt, for instance, 0.002 $year^{-1}$ for slowly creep rock salt, while 0.02 year $^{-1}$ for salt contain high moisture or its crystal surrounded by Carnallite. However, it can be gotten directly, if available data from some well which has been done through the same borehole different times of measurement the diameter change but prefer OBM (oil bas mud) into this hole.

This method has been given good result with case study. See figure (7-21). So, it can be used this empirical method with these parameters to predicated the borehole closure for any case study of Iraq cases.

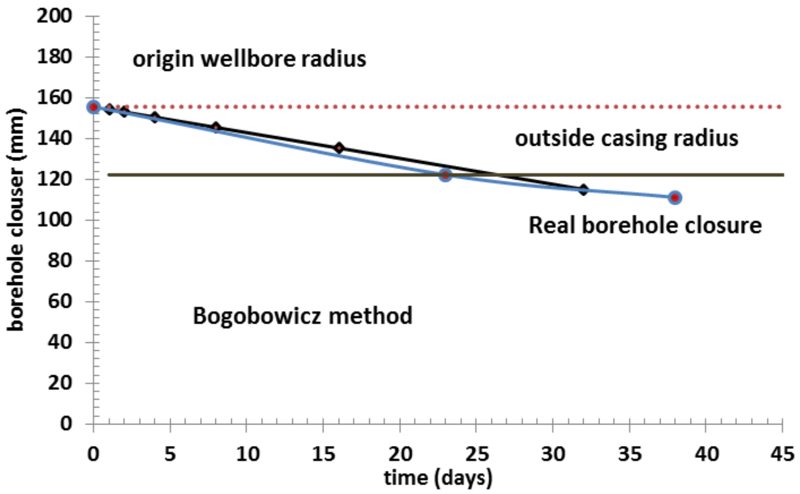


Figure 7-21 comparison borehole closure predicated and real

Chapter 8: Numerical analyses: from experiments to the case studies simulation

8.1. introduction

As it's a clear complexity of borehole instability, which demands to use different tools, and one of these tools, is the numerical tool. These tools are being effectively used to evaluate, analysis, and predication, this tool become the most effective. Furthermore, the results which obtain are more reasonable.

Different software's are being used, as ANSIS, DYANA, ABQUS, actually the borehole instability in rock salt is characterized by time dependence (strain rate dependent) , so the numerical model that used , should be able to calculate viscosity,

Therefore, Gehmadrid codes are used here to evaluate one Iraqi case study depending on the experimental test data. It was started to evaluate using numerical codes on the hollow cylinder test of the Italian rock salt, then using the codes to predict the behaviour of this rock salt with Iraqi case study conditions (temperature, pressures)

8.1. Simulations of the hollow cylinder test HC_IT_RS#2.

There are two tests on the Italian rock salt, were done using new hollow cylinder apparatus, to study the behaviour of rock salt during drilling operation (1st test), while the 2nd test has covered two stages (drilling and creeping).The 2nd test data have used to evaluate the parameters by using "Gehomadrid codes" .The dimensions of specimen that has used (38 mm borehole diameter, 100 mm outside diameter) can be assumed convenient to standard of hollow cylinder dimension test, when the thickness of hollow cylinder equal to borehole diameter, so the experiments have represented the simplified Iraqi case study.

The thickness of hollow cylinder of the Italian rock salt is (31 mm), while the borehole is (38), so it can be assumed, are convenient dimensions.

A symmetric boundary conditions is applied to the symmetric plane strain, was taken one quarter of the borehole, because the hole was assumed circular. See figure (8-1).

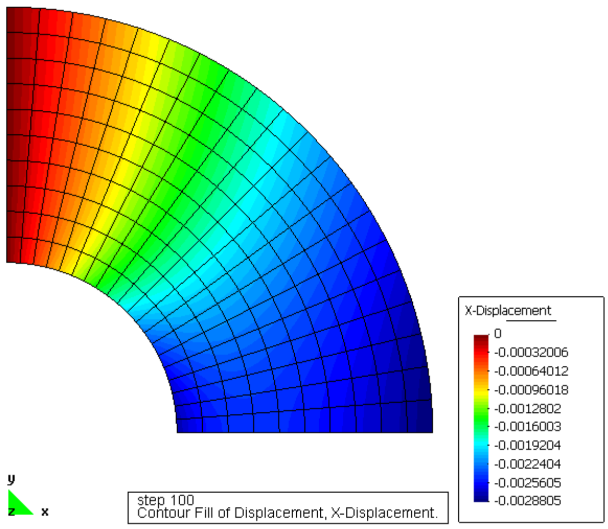


Figure 8-1 symmetric plane model for borehole

The uniform pressures have applied for both internal and external to the x-y plane. After applying the hydrostatic conditions in the hollow cylinder specimen, three steps have developed to simulate the boundary conditions of Iraqi case study.

- Step 1: Recovery the in situ stresses process have applied on the Italian rock salt (30 Mpa external stresses, 30 Mpa axial stresses, and 30 Mpa internal stress), companied by increasing the temperature to (55 C).
- Step 2: the drilling process stage that has impose a uniform wellbore pressure on the inner surface of the borehole which the rock salt has shared other types of rocks this borehole. This step has represented by decreasing the internal pressure for two stages (from 30 Mpa to 25 Mpa, and then 20 Mpa)

- Step 3: Creep step has simulated the real boundary conditions by applied three stages of deviatoric stresses on the rock salt (15 Mpa, 20 Mpa, and 25 Mpa). The internal stresses have decreased while maintain the axial and external stresses at a fixed value (30 Mpa) .Furthermore, it has assumed here, that the far -field region (outside diameter of hollow cylinder), and the inner borehole, remain at a constant temperature (under isothermal conditions). However, the well temperature only affects the near -wellbore region, but for Iraqi case study the change in temperature, is not too big during drilling the new hole, so, the fixed - temperature at the outer boundary as well inner wall of the borehole, is reasonable .

The strain –rate dependent plasticity model based on the Perzyna formulation have used to mimic the hollow cylinder test. There are several material laws that are typically used to model viscoplasticity in a finite elements analysis. Each of these laws represents a different approach and is typically used in different applications, Perzyna model is one of these laws. The Perzyna models adopt a unified creep approach to calculate rate-dependent inelastic strain (creep and plasticity are not calculated separately but instead an inelastic strain is calculated directly, which is assumed that the plastic strain rate is a function of hardening parameter (m), the material viscosity parameter(γ), and the static yield stress (σ_o)

$$\acute{\varepsilon}_{pl} = \boldsymbol{\gamma} * \left(\frac{\boldsymbol{\sigma}}{\boldsymbol{\sigma_o}} - \mathbf{1}\right)^{\mathbf{1}/\boldsymbol{m}} \dots\dots\dots\dots\dots (\mathbf{8-1})$$

The Prezyna model is suitable for high –strain rate loading situation, such as Iraqi case study, to cover a much smaller period of time(days) than long period time for creeping (years), and this model include a yield surface (Mohr coulomb), so the strain rate hardening effect is only after yielding

All the extracted elastic parameters by experiments that were done, have used in the simulation of the hollow cylinder test, (see table), as well the pore pressure was assumed equal to zero. The results have shown agreement between experimental parts with numerical part. See figure (8-2).

Young Modulus (Gpa)	Poisson Ratio	Friction angle	Cohesion(Mpa)	Fluidity (Pa^{-1} S^{-1})	Deviatoric stress (Mpa)
1	0.3	20	3	10^{-15}	(5,10,15)Mpa
1	0.3	20	3	10^{-4}	(20,25)Mpa

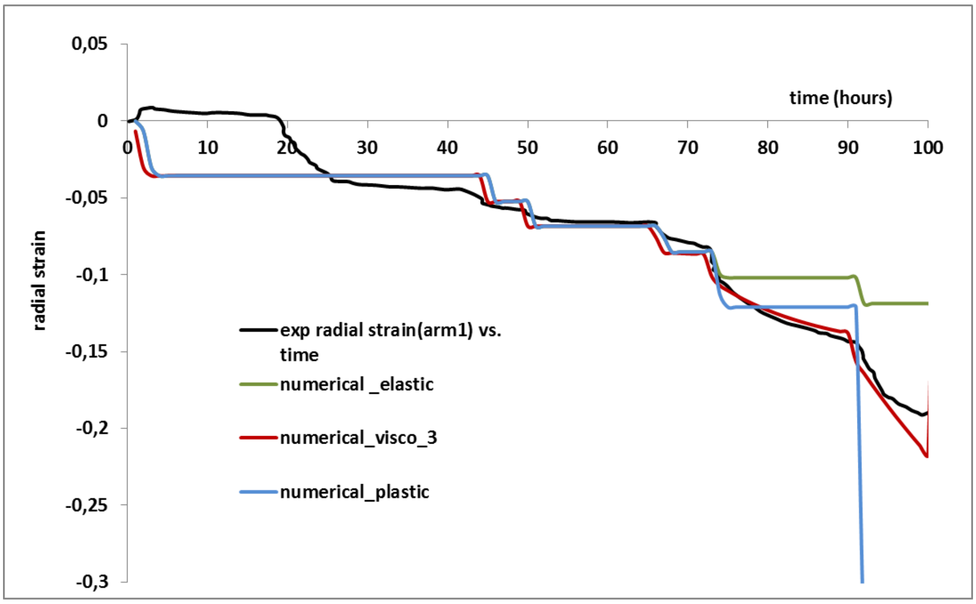
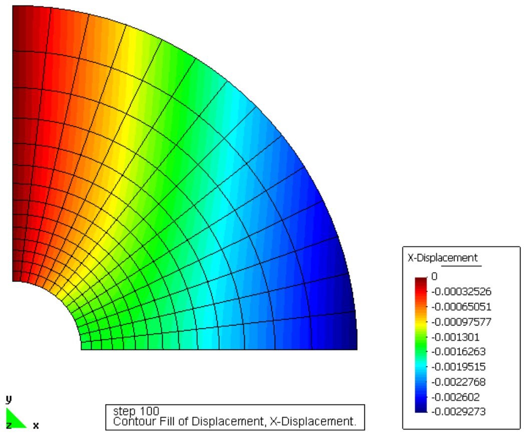


Figure 8-2 comparison between numerical (elastic, plastic, and viscoplastic) with experiments

The figure has shown, three solutions have used, elastic, plastic and viscoplastic, and it's very clear, the Italian rock salt has shown plastic deformation from increment (stress difference ext-int =20 Mpa),and before this increment , it was elastic before that. Furthermore, there are no delays (no viscoplasticity) at time (70 hours), the solution is instantaneous equal to elastic one, while after (70 hours), and there is delay in the viscoplastic solution, however all solutions have shown overestimated value in the in situ stress stage. Furthermore, the fluidity (inverse viscosity) that has used for the first three devaitoric steps (5, 10, 15) Mpa, is (10^{-15} Pa^{-1} S^{-1}) which consider reasonable. On the other hand, the last two steps (20, 25) Mpa have shown viscosity (10^{-4}

Pa^{-1} S^{-1}), might be the water inclusion has affected as well the humidity because from micro logy point of view, the water inclusion test has not done, unfortunately.

In order to simulate the Iraqi boundary conditions, it was used the same dimensions of Iraqi case study but with the same conditions of experimental part, the results have shown the same trend as previous .See figure (8-3).



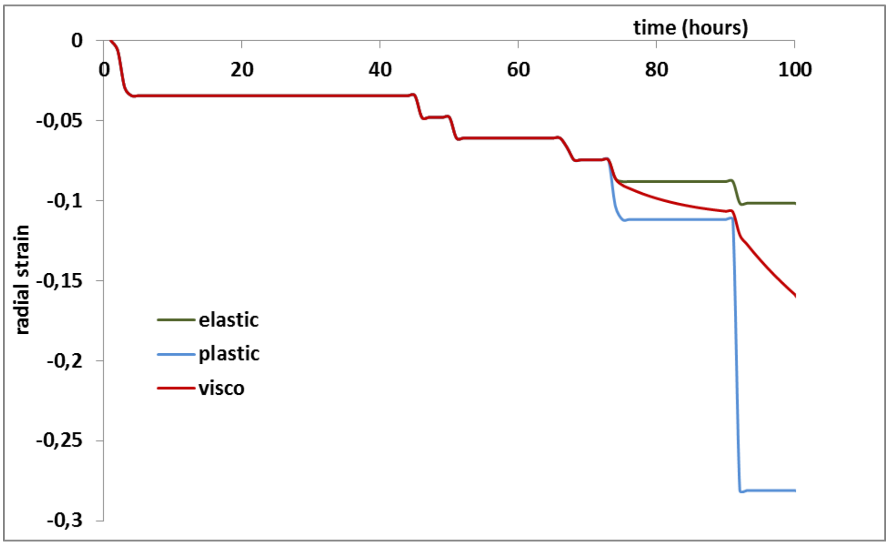


Figure 8-3 the numerical solutions (elastic, plastic, and viscoplastic) in Iraq case study dimension

8.2. Modelling the Iraqi case study depending in HC test HC_IT_RS#2

After the created numerical model has been tested on the experiment of the hollow cylinder to the Italian rock salt, also this model was updated to the real in situ dimensions to the Iraqi rock salt. The other model which has created, here, is to simulate the Iraqi rock salt and to get more predictions for this case study. The results have shown good agreement with real deformation that was happened to the borehole. Three solutions have been applied with same parameters that was used in the model to the experimental data for real dimension, these solution are, elastic, plastic and viscoplastic. See figure (8-4).

The elastic solution has shown, the displacement of the Italian rock salt creep do not reach to the outer of the casing pipe but, it was near from the casing pipe by about (7mm), after more than (500) hours, on the other hand, this solution has shown agreement with the other two solution at the first period from the drilling the borehole, and it has shown clearly deformation (10mm) at this period.

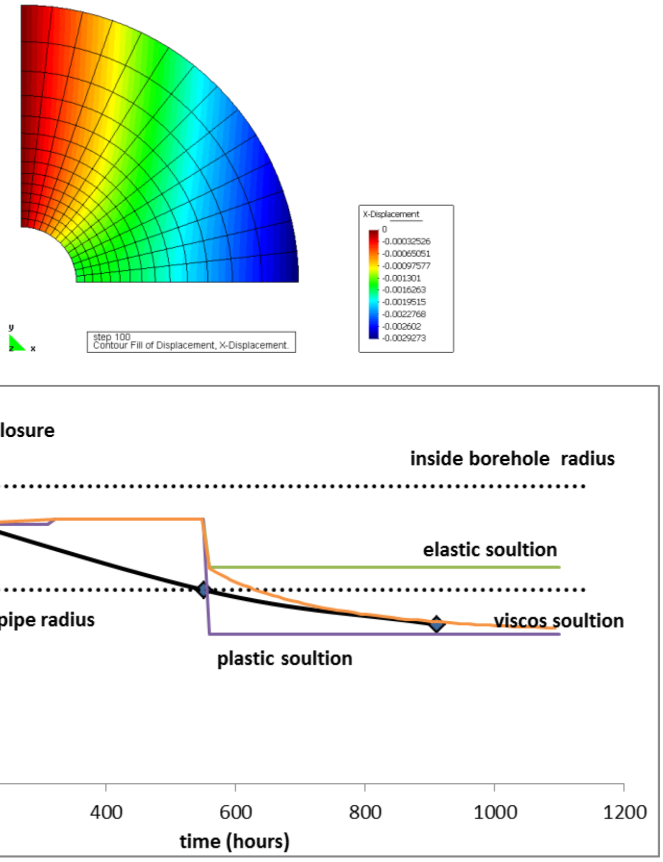


Figure 8-4 numerical solution for real case study

Generally, the first period of drilling borehole has shown the agreement for all solutions, however, the plastic solution has shown more agreement with real borehole closure, because at the same time, when the casing pipes under cement operation(decrease the supported pressure), the rock salt was being started to load the casing pipes.

Actually, more arguments and debate at this point, from practical point of view, there are many related variables that contribute into rock salt deformations, it might be the borehole was elliptical, the stand-off between the casing pipes and borehole, quality of the cement bonds, inter-bedded the rock salt with other harder rocks, the quality the casing pipe ,...etc. This model is based on the experiments of hollow cylinder of the Italian rock salt, which has circular borehole, without casing pipes, cement. So, the plastic solution has shown sudden deformation reached (36 mm), while the viscoplastic solution has shown gradual deformation starting (7mm) far from the outer diameter of the casing pipes, till to (12 mm) deformation inside the casing pipes.

In brief, its reasonable results because, this model give the good analysis, and open the door to cover all other variables, that will be considered.

8.3. Modelling the Iraqi case study adopting elliptical borehole

In this section, it has studied the effect of the elliptical shape (1.25 a/b) for the borehole, and comparing with real case study, using also, Gehomadrid. The parameters which are used here are the same parameters that have used in the circular shape borehole. See figure (8-5).

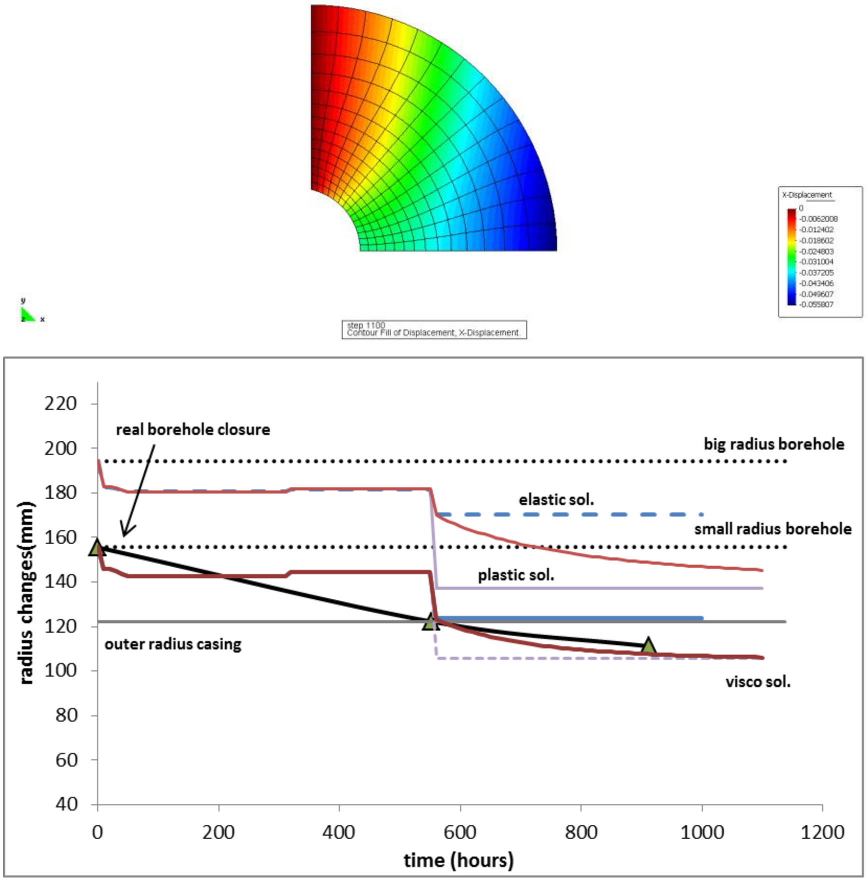


Figure 8-5 numerical solution (elastic, plastic, and viscos) of elliptical shape borehole

It's clear here, the effect elliptical shape of the borehole on the deformation, because the elastic solution has shown the rock salt very near to the casing in the smaller radius regions of the borehole, while the bigger radius is far from the casing pipes. On the other hand, the plastic solution has shown the rock salt loading the casing pipes (550 hours), in the smaller radius regions. The amount of displacement is (17mm) cross the casing pipe; however the bigger radius region is far from the casing pipe. In addition, the viscoplastic solution has shown the same behaviour, while the last step for this solution has shown gradually deformation.

Chapter 9: Conclusion

9.1. Proposed approach

The rock salt is dealt with special care by researchers and geo-structural projects, because its geomechanical properties. The low permeability and porosity features are the main characteristics. These properties give the rock salt the task to play big role in many structural engineering projects , as strategically repositories for radioactive material or hydrocarbons , regeneration electrical power by reserve compressed gas and finally in oil industry as a good barrier for hydrocarbon reservoirs. On the other hand, the rock salt is characterised by the creep that should take with care in every project. The centres of researches, laboratories, universities and oil companies have been trying to cover the rock salt features.

Different structural types of rock salt can be faced, in the oil industry but, the main part which directly faces this type of rocks is exploration sector. The drilling and completion departments are interested in rock salt because those departments face on-going works that needs good planning and implementation and thus developing the most successful solutions. The casing collapsing problem consider one of the hardest drilling problems, because its direct economic effect. This problem is initiated, by the plastic behaviour of some of rock as (rock salt, shale). The complexity of geological structural makes this problem more difficult. The rocks inter-bedded contribute this complexity; as well different variables contribute to create complexity as cement operation, the depths of the drilled hole, types of the drilling fluids, temperature….etc.

Most of experiments that were done, have taken one or two of these factors, but not all, because this complexity. So, this thesis has tried the simplification as it can .The complexity for different case studies, were recorded in the south of Iraq, which was represented by collapsing casing pipes. Different designs of casing pipes, programs of cementing, geological conditions, and drilling muds have been put. It was taken the shared factors for all cases studies, by analysing all data for each one, in order to get the main factors that should be taken. It was selected one case study that covered all shared points for most other cases studies.

First of all, it has analysed the stresses which had created by salt loading on the casing pipes. The mechanical model (curved beam theory) has used to calculate these stresses. It has discovered ,the stresses were bigger than the designed value of the casing pipes, despite the deviatoric stresses was (25 Mpa)(supported casing pipe), however, it might be in real situation the casing pipes is not supported , then the deviator stresses will be bigger than (25 Mpa) because the complexity of cementing operations. In brief, two mechanical models have used, (one based on drilling history of oil wells data and other based on loaded casing experiments), and those models have shown fail the casing pipes by salt .

The experiments are the most important step for rock salt, and because the shortage of Iraqi rock salt material. It has used alternative rock salt to simulate the case studies. The Italian rock salt is selected. Then, it is put a plan to discover the Italian rock salt from mechanical point of view. The main part of this thesis is connected with experimental part, to discover mechanical properties and predict the behaviour the rock salt under Iraqi boundary conditions, then after to give reasonable analysis for the problem.

The experiments have covered the standard part to extract the elastic properties, and advanced part as short and long creep tests under different condition (temperature) to extract the parameters that needed for different empirical models, as well detect the dilatancy boundary for different constant mean stresses. Parts of the experiments need some modifications to measure the deformation, other parts need to develop new tool to measure the deformation inside hollow cylinder rock salt specimen. These improvements have covered the following:

Work to find way to benefit from tri-axial apparatus to get the ability to use strain gauges under high pressures and then able to measure the deformation inside borehole or even external deformation by pasted directly on outside of the specimen. It was designed prototype internal measurement tool for hollow cylinder specimen, and tested under uniaxial elementary creep test, despite the limitation of the cantilever apparatus which represented by low loads. The modifications have given ability to overcome those limitations and give ability applied boundary conditions which has reached to (30 Mpa, 66C).

The hollow cylinder specimen test has represented the most important test because the ability of this test to mimic the boundary conditions by simulating bench scales experiments. The big challenge represents by how apply different loads on the hollow cylinder and measure all deformations inside and outside the hollow cylinder using simple way It was spent big effort to design, create, manufactured, test, and improve.

The new pieces that were designed set in vessel of the tri-axial apparatus. These pieces have included internal, external measurements tools, and plugs to give way to pass the cables reaching to the strain gauges on internal and external tools, under high pressures and temperature using every space through this vessel. Those improvements (external, internal tools, plugs, pedestal with new sealing) are used the space inside the tri-axial apparatus; overcome the limitations that was used hollow cylinder with Hook cell equipment's (Alsayed et al 2002) , because the new design has able to apply creep test for period reaching more than 7days.

It has applied two mechanical models to predicate the casing pipe loads based on the rock salt deformation. One of these models was tested with USA case study, other with experiments that was done on casing pipes. Furthermore, it has used many empirical models to simulate the deformation of rock salt under the same Iraqi boundary conditions, based on the parameters that have extracted from the standard and advanced experiments, which have done on the Italian rock salt.

Many verified tests have done to insure the hollow cylinder apparatus is ready for rock salt test. Two creep tests have been done, both of them consist of two parts (hydrostatic and deviatroic) one to simulated drilling operations, and the other to simulate drilling and creep stages, the first test has extended for more than (190 hours) while the other for more than (100 hours).The results are reasonable because it has used for predication one of Iraqi case study.

9.2. Recommendations

The complexity of Iraqi cases studies should be covered by taken into account the other variables (inter-bedding, cementing, drilling mud effect…etc.), that can be studied by doing more experiments. Actually, these experiments need more raw material of Iraqi rock salt, in specify, the section which inter-bedded with other type of rocks, as anhydrite or shale.

It absolutely need to design a new apparatus or make another modification or improvements to do experiments that related to cementing behind the casing pipe, because in this thesis has assumed bad cementing bonds ,based on the cementing reports recorded by cement bond logs.

As well, it should study the drilling mud effect on rock salt deformation, the drilling mud support the bore hole by applied pressure but the filtration of mud into the rock salt fractures, or grain boundaries ,that lead to activate another type of creeping.

References

Abass, H., Warlick, L., Khan, M., Pardo Techa, C., Tahini, A., Shehri, D., ... & Shobaili, Y. (2011). Evaluation of wellbore stability during drilling and production of open hole horizontal wells in a Carbonate field. Paper SPE-126157-MS presented in the SPE Saudi Arabia Section Technical Symposium, held in Al-Khobar, Saudi Arabia, 9-11 May. DOI: 10.2118/126157-MS.

Abdulhadi, N. O., Germaine, J. T., & Whittle, A. J. (2010). Experimental study of wellbore instability in clays. Journal of Geotechnical and Geoenvironmental Engineering, 137(8), 766-776.

Addis, T., Last, N., Boulter, D., Roca-Ramisa, L., & Plumb, D. (1993). The quest for borehole stability in the Cusiana field, Colombia. Oilfield Review, 5(2), 33-43.

Agergaard, F. A. (2009). Modelling of rock salt creep (Master's thesis, Technical University of Denmark, DTU, DK-2800 Kgs. Lyngby, Denmark).

Alkan, H., Cinar, Y., & Pusch, G. (2007). Rock salt dilatancy boundary from combined acoustic emission and triaxial compression tests. International Journal of Rock Mechanics and Mining Sciences, 44(1), 108-119.

Alsayed, M. I. (2002). Utilising the Hoek triaxial cell for multiaxial testing of hollow rock cylinders. International Journal of Rock Mechanics and Mining Sciences, 39(3), 355-366.

Aqrawi, A. A. M. (1993). Miocene evaporitic sequence of the southern Mesopotamian Basin. Marine and Petroleum geology, 10(2), 172-179.

Aqrawi, A. A., Goff, J. C., & Horbury, A. D. The petroleum geology of Iraq.(2010)

Asadi.A, Parhizgar.N, Momeni.E.(2011).Prediction of Collapse in a Casing and Tubing: with Case Study of Iran. Australian Journal of Basic and Applied Sciences, 5(11): 831-840, 2011 ,ISSN 1991-8178

Ashtiani, H. A., Dusseault, M. B., & Bakhtiar, H. A. (2010). A Novel Geomechanical Analytic Method for Preventing Casing Failure Occurrence. In 14th Oil, Gas & Petrochemical Congress.

ASTM D4406-93: Standard Test Method for Creep of Cylindrical Rock Core Specimens in Triaxial Compression

Bahroudi, A., & Koyi, H. A. (2004). Tectono-sedimentary framework of the Gachsaran Formation in the Zagros foreland basin. Marine and Petroleum Geology, 21(10), 1295-1310.

Bian, Y., Liu, J., Ding, G., Chen, L., Wu, Z., Ran, L., ... & Gou, Y. (2013). Different Methods to Evaluate Strength from Compression Tests for Rock Salt. In Clean Energy Systems in the Subsurface: Production, Storage and Conversion (pp. 281-291). Springer, Berlin, Heidelberg.

Blaber, J., Adair, B., & Antoniou, A. (2015). Ncorr: open-source 2D digital image correlation matlab software. Experimental Mechanics, 55(6), 1105-1122.

Blümling, P., Bernier, F., Lebon, P., & Martin, C. D. (2007). The excavation damaged zone in clay formations time-dependent behaviour and influence on performance assessment. Physics and Chemistry of the Earth, Parts A/B/C, 32(8-14), 588-599.

Bogobowicz, A., Rothenburg, L., & Dusseault, M. B. (1991). Solutions for non-Newtonian flow into elliptical openings. Journal of applied mechanics, 58(3), 820-824.

Bons, P. D., & Urai, J. L. (1996). An apparatus to experimentally model the dynamics of ductile shear zones. Tectonophysics, 256(1-4), 145-164.

Bradley, W. B. (1979). Failure of inclined boreholes. Journal of Energy Resources Technology, 101(4), 232-239.

Bradley, W. B., & Holbrook, P. (1987). U.S. Patent No. 4,710,906. Washington, DC: U.S. Patent and Trademark Office.

Brown, E. T. (1981). Rock characterization, testing & monitoring: ISRM suggested methods.

Carcione, J. M., Helle, H. B., & Gangi, A. F. (2006). Theory of borehole stability when drilling through salt formations. Geophysics, 71(3), F31-F47.

Chan, K. S., Munson, D. E., Bodner, S. R., & Fossum, A. F. (1996). Cleavage and creep fracture of rock salt. Acta Materialia, 44(9), 3553-3565.

Chen, J., Ren, S., Yang, C., Jiang, D., & Li, L. (2013). Self-healing characteristics of damaged rock salt under different healing conditions. Materials, 6(8), 3438-3450.

Cook, J., Frederiksen, R. A., Hasbo, K., Green, S., Judzis, A., Martin, J. W., ... & Noeth, S. (2007). Rocks matter: Ground truth in geomechanics. Oilfield Review, 19(3), 36-55.

Cristescu, N., & Gioda, G. (Eds.). (1994). Visco-plastic behaviour of geomaterials. Springer-Verlag.

Cristescu, N., & Hunsche, U. (1998). Time effects in rock mechanics. New York: Wiley.

De Andrade, J., & Sangesland, S. (2016). Cement sheath failure mechanisms: numerical estimates to design for long-term well integrity. Journal of Petroleum Science and Engineering, 147, 682-698.

DeVries, K. L., Mellegard, K. D., & Callahan, G. D. (2002). Salt damage criterion proof-of-concept research. Respec, Inc.(US).

Drury, M. R., & Urai, J. L. (1990). Deformation-related recrystallization processes. Tectonophysics, 172(3-4), 235-253.

Du, C., Yang, C., Yao, Y., Li, Z., & Chen, J. (2012). Mechanical behaviour of deep rock salt under the operational conditions of gas storage. Int J Earth Sci Eng, 5(6), 1670-1676.

Dunlop, J., Isangulov, R., Aldred, W. D., Sanchez, H. A., Flores, J. L. S., Herdoiza, J. A., ... & Luppens, C. (2011, January). Increased rate of penetration through automation. In SPE/IADC Drilling Conference and Exhibition. Society of Petroleum Engineers.

Dusseault, M. B., Bruno, M. S., & Barrera, J. (1998, January). Casing shear: causes, cases, cures. In SPE International Oil and Gas Conference and Exhibition in China. Society of Petroleum Engineers.

Dusseault, M. B., Maury, V., Sanfilippo, F., & Santarelli, F. J. (2004, January). Drilling through salt: constitutive behavior and drilling strategies. In Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium (NARMS). American Rock Mechanics Association.

Düsterloh, U., & Lux, K. H. (2012). Impact of lab tests on rock salt for an economical optimization of salt caverns. Proceedings: Mechanical Behavior of Salt VII, 343-352.

Eberhardt, E., Stead, D., Stimpson, B., & Lajtai, E. Z. (1998). The effect of neighbouring cracks on elliptical crack initiation and propagation in uniaxial and triaxial stress fields. Engineering Fracture Mechanics, 59(2), 103-115.

Elkadi, A. S. K. (2005). Fracture scaling of concrete under multiaxial compression.

Ewy, R. T., & Cook, N. G. W. (1990, October). Deformation and fracture around cylindrical openings in rock—I. Observations and analysis of deformations. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 27, No. 5, pp. 387-407). Pergamon.

Farmer, I. W., & Gilbert, M. J. (1984, October). Time dependent strength reduction of rock salt. In Proceedings of the First Conference on the Mechanical Behavior of Salt (pp. 3-18).

Feng, B., Xu, M. L., Zhao, T. F., Zhang, Z. J., & Lu, T. J. (2010). Triaxial extensometer for volumetric strain measurement in a hydro-compression loading test for foam materials. Measurement Science and Technology, 21(11), 115705.

Filimonov, Y. L., Lavrov, A. V., Shafarenko, Y. M., & Shkuratnik, V. L. (2001). Memory effects in rock salt under triaxial stress state and their use for stress measurement in a rock mass. Rock mechanics and rock engineering, 34(4), 275-291.

Firme, P. A., Roehl, D., & Romanel, C. (2016). An assessment of the creep behaviour of Brazilian salt rocks using the multi-mechanism deformation model. Acta Geotechnica, 11(6), 1445-1463.

Fjaer, E., Holt, R. M., Horsrud, P., Raaen, A. M., & Risnes, R. (2008). Geological aspects of petroleum related rock mechanics. Developments in petroleum science, 53, 103-133..

Fredrich, J. T., & Fossum, A. F. (2002). Large-scale three-dimensional geomechanical modeling of reservoirs: examples from California and the deepwater Gulf of Mexico. Oil & Gas Science and Technology, 57(5), 423-431.

Frost, H. J., & Ashby, M. F. (1982). Deformation-mechanism maps: the plasticity and creep of metals and ceramics.

Fuenkajorn, Kittitep,(1988). Borehole closure in salt . PhD.thesis

Gangi, A. F. (1981). A Constitutive Equation for One-Dimensional Transient and Steady State Flow of Solids. Mechanical behavior of crustal rocks: the Handin volume, 275-285.

Ge, W., Chen, M., Jin, Y., Zhang, F., Lu, Y., Yang, P., ... & Zeng, H. (2011). Analysis of the external pressure on casings induced by salt-gypsum creep in build-up sections for horizontal wells. Rock mechanics and rock engineering, 44(6), 711.

Ghoreychi, M., Daupley, X., & Laouafa, F. (2012). Creep and damage impact on long-term stability of underground structures in salt formations. Mechanical Behaviour of Salt VII, 283.

Grzybowski, Ł. U. K. A. S. Z., Wilkosz, P. A. W. E. Ł., & Flisiak, D. (2008). Mechanical properties of rock salt from Mogilno salt dome. Gospodarka Surowcami Mineralnymi [Przegląd Solny], 24(3), 2.

Hackney, R. M. (1985, January). A new approach to casing design for salt formations. In SPE/IADC Drilling Conference. Society of Petroleum Engineers.

Haimson, B., & Kovacich, J. (2003). Borehole instability in high-porosity Berea sandstone and factors affecting dimensions and shape of fracture-like breakouts. Engineering geology, 69(3-4), 219-231.

Hampel, A., Hunsche, U., Weidinger, P., & Blum, W. (1998). Description of the creep of rock salt with the composite model-II. Steady-State creep. Series on rock and soil mechanics, 287-299.

Handin, J., & Hager Jr, R. V. (1958). Experimental deformation of sedimentary rocks under confining pressure: tests at high temperature. AAPG Bulletin, 42(12), 2892-2934.

Hansen, F. D., & Carter, N. L. (1980, May). Creep of rock salt at elevated temperature. In 21st US Symp. on Rock Mechanics (pp. 28-30). University of Missouri-Rolla.Cristescu, N. (1987, October). Elastic/viscoplastic constitutive equations for rock. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 24, No. 5, pp. 271-282). Pergamon.

Hashemi, S. S., Melkoumian, N., & Taheri, A. (2015). A borehole stability study by newly designed laboratory tests on thick-walled hollow cylinders. Journal of Rock Mechanics and Geotechnical Engineering, 7(5), 519-531.

Hawkes, C. D., Bachu, S., Haug, K., & Thompson, A. W. (2005, May). Analysis of in-situ stress regime in the Alberta Basin, Canada, for performance assessment of CO2 geological sequestration sites. In Fourth Annual Conference on Carbon Capture and Sequestration (pp. 2-5).

Heerema, S. (2009). A magmatic model for the origin of large salt formations. Journal of Creation, 23(3), 116-118.

Hobbs, D. W. (1965). An assessment of a technique for determining the tensile strength of rock. British Journal of Applied Physics, 16(2), 259.

Homke, S., Vergés, J., Garcés, M., Emami, H., & Karpuz, R. (2004). Magnetostratigraphy of Miocene–Pliocene Zagros foreland deposits in the front of the Push-e Kush arc (Lurestan Province, Iran). Earth and Planetary Science Letters, 225(3-4), 397-410.

Horseman, S. T., & Handin, J. (1990). Triaxial-compression tests on rocksalt at temperatures from 50° to 200° c and strain rates from 10− 4 to 10− 9/s (pp. 103-110). American Geophysical Union.

Hoskins, E. R. (1969, January). The failure of thick-walled hollow cylinders of isotropic rock. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 6, No. 1, pp. 99-125). Pergamon.

Hou, B., Chen, M., Jin, Y., Liu, X. M., & Chen, G. P. (2011, September). The method for overcoming salt formations creep by using the relationship of drilling fluids density and chloride ion content. In International young scholars' symposium on rock mechanics (pp. 113-116).

Hou, Z. (2003). Mechanical and hydraulic behavior of rock salt in the excavation disturbed zone around underground facilities. International Journal of Rock Mechanics and Mining Sciences, 40(5), 725-738.

Hudson, J. A. (1969, January). Tensile strength and the ring test. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 6, No. 1, pp. 91-97). Pergamon.

Hunsche, U., & Albrecht, H. (1990). Results of true triaxial strength tests on rock salt. Engineering Fracture Mechanics, 35(4-5), 867-877.

Hunsche, U., & Schulze, O. (2003, November). The dilatancy concept–a basis for the modelling of coupled TMH processes in rock salt. In European Commission CLUSTER Conference on the Impact of EDZ on the Performance of Radioactive Waste Geological Repositories (pp. 3-5).

Jackson, M. P., & Talbot, C. J. (1986). External shapes, strain rates, and dynamics of salt structures. Geological Society of America Bulletin, 97(3), 305-323.

Jaeger, J. C., & Hoskins, E. R. (1966). Stresses and failure in rings of rock loaded in diametral tension or compression. British Journal of Applied Physics, 17(5), 685.

Jin, J., & Cristescu, N. D. (1998). An elastic/viscoplastic model for transient creep of rock salt. International Journal of Plasticity, 14(1-3), 85-107.

Khaledi, K., Datcheva, M., & Schanz, T. GEOMECHANICAL BEHAVIOUR OF ROCK SALT: ASSESSMENT OF EXISTING MODELS.

Koupriantchik, D., Hunt, S. P., Boult, P. J., & Meyers, A. G. (2005, August). Geomechanical modeling of salt diapirs: 3D salt structure from the Officer Basin, South Australia. In Central Australian Basins Symposium.

Labiouse, V., Sauthier, C., & You, S. (2014). Hollow cylinder simulation experiments of galleries in Boom Clay formation. Rock Mechanics and Rock Engineering, 47(1), 43-55.

Lambe, T. W., & Whitman, R. V. (1991). Soil Mechanics (p. 29).

Lang, J., Li, S., & Zhang, J. (2011, January). Wellbore stability modeling and real-time surveillance for deepwater drilling to weak bedding planes and depleted reservoirs. In SPE/IADC Drilling Conference and Exhibition. Society of Petroleum Engineers.

Langer, M. "Geotechnical investigation methods for rock salt." Bulletin of the International Association of Engineering Geology-Bulletin de l'Association Internationale de Géologie de l'Ingénieur 25.1 (1982): 155-164.

Langer, M. (1984, October). The rheological behavior of rock salt. In Proc. 1st Conf. Mech. Beh. of Salt (pp. 201-240).

Lao, K., Bruno, M. S., & Serajian, V. (2012, April). Analysis of salt creep and well casing damage in high pressure and high temperature environments. In Offshore Technology Conference. Offshore Technology Conference.

Lavrov, A., & Torsæter, M. (2016). Physics and mechanics of primary well cementing. Springer.

Lee, D. H., Juang, C. H., & Lin, H. M. (2002). Yield surface of Mu-San sandstone by hollow cylinder tests. Rock mechanics and rock engineering, 35(3), 205-216.

Lee, D. H., Juang, C. H., Chen, J. W., Lin, H. M., & Shieh, W. H. (1999). Stress paths and mechanical behavior of a sandstone in hollow cylinder tests. International Journal of Rock Mechanics and Mining Sciences, 36(7), 857-870.

Lee, M., & Haimson, B. (1993, December). Laboratory study of borehole breakouts in Lac du Bonnet granite: a case of extensile failure mechanism. In International journal of rock mechanics and mining sciences & geomechanics abstracts (Vol. 30, No. 7, pp. 1039-1045). Pergamon.

Leite, M. H., Gill, D. E., & Corthésy, R. (1998). Experimental and numerical evaluation of stress redistribution in thick-walled rocksalt cylinders. International Journal of Rock Mechanics and Mining Sciences, 35(3), 367-383.

Li, H H ; Matula, R A ; Yang, J M ; Hume, H R ; Shakoor,1981.Thermo-physical properties. In Physical Properties Data for Rock Salt.

Liang, W. G., Xu, S. G., & Zhao, Y. S. (2006). Experimental study of temperature effects on physical and mechanical characteristics of salt rock. Rock mechanics and rock engineering, 39(5), 469-482.

Liang, W. G., Yang, C. H., Zhao, Y. S., Dusseault, M. B., & Liu, J. (2007). Experimental investigation of mechanical properties of bedded salt rock. International Journal of Rock Mechanics and Mining Sciences, 44(3), 400-411.

Liang, W. G., Zhao, Y. S., Xu, S. G., & Dusseault, M. B. (2011). Effect of strain rate on the mechanical properties of salt rock. International Journal of Rock Mechanics and Mining Sciences, 48(1), 161-167.

Lin, Y. H., Deng, K. H., Zeng, D. Z., Zhu, H. J., Zhu, D. J., Qi, X., & Huang, Y. (2014). Theoretical and experimental analyses of casing collapsing strength under non-uniform loading. Journal of Central South University, 21(9), 3470-3478.

Lin, Y., Qi, X., Deng, K., Zeng, D., Zhu, H., & Zhu, D. (2013). Empirical formula given for collapse resistance of worn casing under nonuniform loading. Oil & Gas Journal, 111(2), 60-60.

Liu, J. X., Zhu, W. C., Liu, J., Sheng, J. C., Brady, B. H., & Tang, C. A. (2007). Simulation of progressive borehole failure at multi-lateral junctions. Petroleum Science and Technology, 25(9), 1185-1198.

Lugli, S., Schreiber, B. C., & Triberti, B. (1999). Giant polygons in the Realmonte mine (Agrigento, Sicily): evidence for the desiccation of a Messinian halite basin. Journal of Sedimentary Research, 69(3).

Lux, K. H. (2009). Design of salt caverns for the storage of natural gas, crude oil and compressed air: Geomechanical aspects of construction, operation and abandonment. Geological Society, London, Special Publications, 313(1), 93-128.

M.Hosseini, Experimental study of hydro-mechanical behaviour of porous rock in relation to the excavation problems.

Ma, L. J., Liu, X. Y., Fang, Q., Xu, H. F., Xia, H. M., Li, E. B., ... & Li, W. P. (2013). A new elasto-viscoplastic damage model combined with the generalized Hoek–Brown failure criterion for bedded rock salt and its application. Rock mechanics and rock engineering, 46(1), 53-66.

Mahmoudi, E., Khaledi, K., von Blumenthal, A., König, D., & Schanz, T. (2016). Concept for an integral approach to explore the behavior of rock salt caverns under thermo-mechanical cyclic loading in energy storage systems. Environmental Earth Sciences, 75(14), 1069.

Marcelo Venturino, "Four key mechanisms to ensure a successful cementing design " (www.wellcementingconsulting.com)

Mellegard, K. D., & Pfeifle, T. W. (1999). Laboratory evaluation of mechanical properties of rock using an automated triaxial compression test with a constant mean stress criterion. In Nondestructive and Automated Testing for Soil and Rock Properties. ASTM International.

Moeck, I., & Backers, T. (2011). Fault reactivation potential as a critical factor during reservoir stimulation. First break, 29(5), 73-80.

Mogi, K. (1981). Flow and fracture of rocks under general triaxial compression. Applied Mathematics and Mechanics, 2(6), 635-651.

Monfared, M., Delage, P., Sulem, J., Mohajerani, M., Tang, A. M., & De Laure, E. (2011). A new hollow cylinder triaxial cell to study the behavior of geo-materials with low permeability. International Journal of Rock Mechanics and Mining Sciences, 48(4), 637-649.

Morgan, H. S., & Wawersik, W. R. (1991, January). The use of thick-walled hollow cylinder creep tests for evaluating flow criteria for rock salt. In 7th ISRM Congress. International Society for Rock Mechanics.

Muhammad .N (2015).An experimental study exploring effects of pressure and stress relaxation, PhD,thesis.

Munson, D. E. (1979). Preliminary deformation-mechanism map for salt (with application to WIPP) (No. SAND-79-0076). Sandia Labs., Albuquerque, NM (USA).

Munson, D. E. (2004, January). MD constitutive model parameters defined for gulf coast salt domes and structures. In Gulf Rocks 2004, the 6th North America Rock Mechanics Symposium (NARMS). American Rock Mechanics Association.

Numan, N. M. (1997). A plate tectonic scenario for the Phanerozoic succession in Iraq. Iraqi Geological Journal, 30(2), 85-110.

O'Kelly, B. C., & Naughton, P. J. (2003). Development of the University College Dublin hollow cylinder apparatus. In Proceedings 56th Canadian Geotechnical Conference, Winnipeg, Ontario.

Packers.T, (2013).Borehol e Geo-mechanics and Well, IGA Academy report .

Papamichos, E. (2010). Analysis of borehole failure modes and pore pressure effects. Computers and Geotechnics, 37(1-2), 141-152.

Papamichos, E., Tronvoll, J., Skjærstein, A., & Unander, T. E. (2010). Hole stability of Red Wildmoor sandstone under anisotropic stresses and sand production criterion. Journal of Petroleum Science and Engineering, 72(1-2), 78-92.

Paraschiv-Munteanu, I., & Cristescu, N. D. (2001). Stress relaxation during creep of rocks around deep boreholes. International Journal of Engineering Science, 39(7), 737-754.

Pašić, B., Gaurina Međimurec, N., & Matanović, D. (2007). Wellbore instability: causes and consequences. Rudarsko-geološko-naftni zbornik, 19(1), 87-98.

Peach, C. J., & Spiers, C. J. (1996). Influence of crystal plastic deformation on dilatancy and permeability development in synthetic salt rock. Tectonophysics, 256(1-4), 101-128.

Peach, C. J., Spiers, C. J., & Trimby, P. W. (2001). Effect of confining pressure on dilatation, recrystallization, and flow of rock salt at 150 C. Journal of Geophysical Research: Solid Earth, 106(B7), 13315-13328.

Peng, S., & Zhang, J. (2007). Engineering geology for underground rocks. Springer Science & Business Media.

Pfeifle, T. W., Mellegard, K. D., & Senseny, P. E. (1983). Preliminary constitutive properties for salt and nonsalt rocks from four potential repository sites (No. ONWI-450). RE/SPEC, Inc., Rapid City, SD (USA).

Pfeifle, T. W., Mellegard, K. D., Skaug, N. T., & Bruno, M. S. (2001). An Investigation of the Integrity of Cemented Casing Seals with Application to Salt Cavern Sealing and Abandonment (No. DOE/FEW 3692-2). National Petroleum Technology Office, Tulsa, OK (US).

Poiate, E., da Costa, A. M., & Falcao, J. L. (2006). CENPES uses FEA to design casing for Santos basin. Oil & gas journal, 104(22), 52-52.

Popp, T., & Kern, H. (2000). Monitoring the state of microfracturing in rock salt during deformation by combined measurements of permeability and P-and S-wave velocities. Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy, 25(2), 149-154.

Rahimi, S., & Hosseini, M. (2015). Laboratory studies of creep behavior on thick-walled hollow cylindrical salt rock specimens. Arabian Journal of Geosciences, 8(8), 5949-5957.

Ratigan, J. L., Van Sambeek, L. L., DeVries, K. L., & Nieland, J. D. (1991). The influence of seal design on the development of the disturbed rock zone in the WIPP alcove seal tests. *RSI-0400, prepared by RE/SPEC Inc., Rapid City, SD, for Sandia National Laboratories, Albuquerque, NM*.

Roy, D. G., & Singh, T. N. (2016). Effect of heat treatment and layer orientation on the tensile strength of a crystalline rock under Brazilian test condition. Rock Mechanics and Rock Engineering, 49(5), 1663-1677.

Salehi, S., Hareland, G., Dehkordi, K. K., Ganji, M., & Abdollahi, M. (2009). Casing collapse risk assessment and depth prediction with a neural network system approach. Journal of Petroleum Science and Engineering, 69(1-2), 156-162.

Salehi, S., Hareland, G., Ganji, M., Dehkordi, K. K., & Abdullahi, M. (2007, January). Using Neural Network System for Casing Collapse Occurrence and Its Depth Prediction in a Middle-Eastern Carbonate Field. In SPE/IADC Middle East Drilling and Technology Conference. Society of Petroleum Engineers.

Santarelli, F. J., Brown, E. T., & Maury, V. (1986, December). Analysis of borehole stresses using pressure-dependent, linear elasticity. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 23, No. 6, pp. 445-449). Pergamon.

Schulze, O., Popp, T., & Kern, H. (2001). Development of damage and permeability in deforming rock salt. Engineering Geology, 61(2-3), 163-180.

Senseny, P. E., Hansen, F. D., Russell, J. E., Carter, N. L., & Handin, J. W. (1992, July). Mechanical behaviour of rock salt: phenomenology and micromechanisms. In International journal of rock mechanics and mining sciences & geomechanics abstracts (Vol. 29, No. 4, pp. 363-378). Pergamon.

Senseny, P. E., Mellegard, K. D., & Wagner, L. A. (1989). Hollow cylinder tests on natural rock salt. Geotechnical Testing Journal, 12(2), 157-162.

Singh, A., Kumar, C., Kannan, L. G., Rao, K. S., & Ayothiraman, R. (2017). Rheological Behaviour of Rock Salt Under Uniaxial Compression. Procedia Engineering, 173, 639-646.

Sissakian, V. K. (2013). Geological evolution of the Iraqi Mesopotamia Foredeep, inner platform and near surroundings of the Arabian Plate. Journal of Asian Earth Sciences, 72, 152-163.

Speranza, G., Cosentino, D., Tecce, F., & Faccenna, C. (2013). Paleoclimate reconstruction during the Messinian evaporative drawdown of the Mediterranean Basin: insights from microthermometry on halite fluid inclusions. Geochemistry, Geophysics, Geosystems, 14(12), 5054-5077.

Spiers, C. J., Urai, J. L., & Lister, G. S. (1988). The effect of brine (inherent or added) on rheology and deformation mechanisms in salt rock. In Proc. Second Conf. on Mechanical Behavior of Salt. Trans. Tech. Publ., Hanover, W. Germany (pp. 89-102).

Sriapai, T., Walsri, C., & Fuenkajorn, K. (2012). Effect of temperature on compressive and tensile strengths of salt. ScienceAsia, 38(2), 166-174.

Staelens, S., Galle, T., De Waele, W., & De Baets, P. (2012). Analysis of API 5C3 failure prediction formulae for casing and tubing. In Sustainable Construction and Design (SCAD-2012) (Vol. 3, No. 1, pp. 80-88). Ghent University, Laboratory Soete.

Stanier, S. A., Blaber, J., Take, W. A., & White, D. J. (2015). Improved image-based deformation measurement for geotechnical applications. Canadian Geotechnical Journal, 53(5), 727-739.

Stormont, J. C., & Fuenkajorn, K. (1993). Dilation-induced permeability changes in rock salt (No. SAND--93-2670C; CONF-940506--1). Sandia National Labs., Albuquerque, NM (United States).

Sun, L., Gao, D., & Zhu, K. (2012). Models & tests of casing wear in drilling for oil & gas. Journal of Natural Gas Science and Engineering, 4, 44-47.

Tien, Y. M., Kuo, M. C., & Juang, C. H. (2006). An experimental investigation of the failure mechanism of simulated transversely isotropic rocks. International Journal of Rock Mechanics and Mining Sciences, 43(8), 1163-1181.

Tingay, M., Reinecker, J., & Müller, B. (2008). Borehole breakout and drilling-induced fracture analysis from image logs. World Stress Map Project, 1-8.

Urai, J. L., & Spiers, C. J. (2007, May). The effect of grain boundary water on deformation mechanisms and rheology of rocksalt during long-term deformation. In Proc. 6th Conf. Mech. Beh. of Salt (pp. 149-158).

Urai, J. L., Schléder, Z., Spiers, C. J., & Kukla, P. A. (2008). Flow and transport properties of salt rocks. Dynamics of complex intracontinental basins: the Central European Basin system, 277-290.

Valdueza Lozano, S. (2003). New Hollow Cylinder Torsional Apparatus (HCTA).

Van Keken, P. E., Spiers, C. J., Van den Berg, A. P., & Muyzert, E. J. (1993). The effective viscosity of rocksalt: implementation of steady-state creep laws in numerical models of salt diapirism. Tectonophysics, 225(4), 457-476.

Van Sambeek, L. L., Ratigan, J. L., & Hansen, F. D. (1993, December). Dilatancy of rock salt in laboratory tests. In International journal of rock mechanics and mining sciences & geomechanics abstracts (Vol. 30, No. 7, pp. 735-738). Pergamon.

Wang, G. (2004). A new constitutive creep-damage model for salt rock and its characteristics. International Journal of Rock Mechanics and Mining Sciences, 41, 61-67.

Wang, G., Xing, W., Liu, J., & Xie, L. (2013). Comparison of Triaxial Compression Short-Term Strength Tests and Data Processing Methods for Rock Salt. In Clean Energy Systems in the Subsurface: Production, Storage and Conversion (pp. 305-315). Springer, Berlin, Heidelberg.

Wang, G., Xing, W., Liu, J., & Xie, L. (2013). Comparison of Triaxial Compression Short-Term Strength Tests and Data Processing Methods for Rock Salt. In Clean Energy Systems in the Subsurface: Production, Storage and Conversion (pp. 305-315). Springer, Berlin, Heidelberg.

Wang, G., Zhang, L., Zhang, Y., & Ding, G. (2014). Experimental investigations of the creep–damage–rupture behaviour of rock salt. International Journal of Rock Mechanics and Mining Sciences, 66, 181-187.

Wang, H., & Samuel, R. (2016). 3D geomechanical modeling of salt-creep behavior on wellbore casing for presalt reservoirs. SPE Drilling & Completion, 31(04), 261-272.

Wang, T., Yan, X., Yang, X., Cao, X., & Huang, H. (2012). Geo mechanical analysis of casing failure in bedded rock salt formation. Res. J. Appl. Sci. Eng. Technol, 4(17), 3069-3077.

Wawersik, W. R., & Hannum, D. W. (1980). Mechanical behavior of New Mexico rock salt in triaxial compression up to 200 C. Journal of Geophysical Research: Solid Earth, 85(B2), 891-900.

Weijermars, R., Jackson, M. P. A., & Dooley, T. P. (2014). Quantifying drag on wellbore casings in moving salt sheets. Geophysical Journal International, 198(2), 965-977.

Weijermars, R., Jackson, M. P. A., & Van Harmelen, A. (2013). Closure of open wellbores in creeping salt sheets. Geophysical Journal International, 196(1), 279-290.

Wetchasat, K. (2002). Assessment of mechanical performance of rock salt formations for nuclear waste repository in northeastern Thailand (Doctoral dissertation, MS thesis, Suranaree University of Technology, Thailand).

Willson, S. M., Fossum, A. F., & Fredrich, J. T. (2002, January). Assessment of salt loading on well casings. In IADC/SPE Drilling Conference. Society of Petroleum Engineers.

Willson, S. M., Last, N. C., Zoback, M. D., & Moos, D. (1999, January). Drilling in South America: a wellbore stability approach for complex geologic conditions. In Latin American and Caribbean petroleum engineering conference. Society of Petroleum Engineers.

Wiprut, D., & Zoback, M. (2000). Constraining the stress tensor in the Visund field, Norwegian North Sea: Application to wellbore stability and sand production. International Journal of Rock Mechanics and Mining Sciences, 37(1-2), 317-336..

Wisetsaen, S., Walsri, C., & Fuenkajorn, K. (2015). Effects of loading rate and temperature on tensile strength and deformation of rock salt. International Journal of Rock Mechanics and Mining Sciences, (73), 10-14.)

Wittke, W. (2014). Rock mechanics based on an anisotropic jointed rock model (AJRM). John Wiley & Sons.

Xing, W., Zhao, J., Düsterloh, U., Brückner, D., Hou, Z., Xie, L., & Liu, J. (2014). Experimental study of mechanical and hydraulic properties of bedded rock salt from the Jintan location. Acta Geotechnica, 9(1), 145-151.

Yimsiri, S., Soga, K., & Chandler, S. G. (2005). Cantilever-type local deformation transducer for local axial strain measurement in triaxial test. Geotechnical Testing Journal, 28(5), 445-451.

Zhang, J., Standifird, W. B., & Lenamond, C. (2008, January). Casing ultradeep, ultralong salt sections in deep water: A case study for failure diagnosis and risk mitigation in record-depth well. In SPE annual technical conference and exhibition. Society of Petroleum Engineers.

Zhao, H., Chen, M., & Wang, J. (2011). Salt loading on casing in cased wellbore sections. International Journal of Rock Mechanics and Mining Sciences, 48(3), 501-505.

Zhao, J., Hou, M. Z., & Xing, W. (2013). Parameter determination for the Constitutive Model Lubby2 and Strength Model Hou based on laboratory tests on rock salt samples from Jintan, PR China. In Clean Energy Systems in the Subsurface: Production, Storage and Conversion (pp. 293-304). Springer, Berlin, Heidelberg..

Zhu, W., & Gu, S. Q. (2013). Casing mechanism of engineering hazards in a oil field in central China. Environmental earth sciences, 70(2), 869-875.

Ziegler, M. A. (2001). Late Permian to Holocene paleofacies evolution of the Arabian Plate and its hydrocarbon occurrences.