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The impact of poor cementing casing damage: A numerical simulation study

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Abstract

A good knowledge of the parameters causing casing damage is critically important due to vital role of casing during the life of a well. Cement sheath, which fills in the gap between the casing and wellbore wall, has a profound effect on the resistance of the casing against applied loads. Most of the empirical equations proposed to estimate the collapse resistance of casing ignore the effects of the cement sheath on collapse resistance and rather assume uniform loading on the casing. This paper aims to use numerical modeling to show how a bad cementing job may lead to casing damage. Two separate cases were simulated where the differences between good and bad cementation on casing resistance were studied. In both cases, the same values of stresses were applied at the outer boundary of the models. The results revealed that a good cementing job can provide a perfect sheath against the tangential stress induced by far-field stresses and reduce the chance of casing to be damaged.

Keywords: *Cementing Job, Casing damage, ABAQUS, Finite Element, Southern part of Iran.*

1. Introduction

Casing stability analysis is an important part of wellbore design, and therefore it is necessary to predict the casing response in wellbores drilled in complicated geological conditions. The casing is usually subjected to various loads in short term during drilling and long term during production life of the field. Buckling due to axial load and burst and collapse as a result of high internal and external pressures, respectively, are examples of excessive loads causing casing failure [1]. Casing damage is a reported incident in oil and gas wells [2]. This may happen during reservoir depletion due to excessive non-uniform load caused by buckling or changes in temperature gradient [3]. Conventional collapse design fails to consider the effect of non-uniform loads which is known to be one of the most common reasons of casing damage. Poor cementation jobs, voids and eccentrically are the examples of situations where casing may undergo non-uniform loading.

One of the most conventional criteria of casing design is yield strengths predicted by empirical equations. Different parameters are included in any of these equations where elastic or plastic behaviors are assumed for prediction of casing resistance. However, these equations are accurate as long as a uniform load is applied on the casing under symmetric conditions. In addition, many of them are not able to consider the interaction of casing, cement and formations on the strength of casing [4]. Thus due to complexity of casing failure phenomenon, a simple equation cannot give any useful results and rather a more complex approach is required to study the entire parameters involved in such catastrophic incident [5, 6].

Numerical methods are useful tools recently used to study those mechanisms causing the casing to fail. There have been many studies on the applications of numerical analysis in casing collapse modeling where stress distribution inside the cement and the casing has been analyzed under perfect conditions [5]. In fact, it was shown that maximum VonMises stress on casing in the wellbores cemented by high thermal properties does not increase as eccentricity increases. However, there will be a significant change in maximum VonMises stress when eccentricity increases in the wellbores cemented by low thermal properties. This is while, in reality, most of the cements used conventionally in the industry are low thermal cements. Moreover, effects of voids, cement channels and pore pressure variation on the casing integrity need more studies [4]. Berger et al., [4] and Fleckenstein et al., [6] neglected the effect of pore pressure and developed different numerical models to study the effect of non-uniform loads on the casing failure.

In this paper, numerical modeling is used to simulate interaction of casing, cement and formations where perfect and poor cementing jobs are taken into consideration to assess how channels and voids can cause the casing to fail. The data used to develop current paper belongs to one of the fields located in southern part of Iran. However, the name of the field cannot be released due to confidentiality matters.

Casing damage has been reported in this field since the past few decades. There is no trend for the number of casings damaged in this field to relate the damages to the age of the pipe, bad cementing job or sanding production problems. Previous studies available through some internal reports suggested that there is no single mechanism responsible for the collapse of casing in this field, and rather it is might be due to a combination of different mechanisms. A summary of the field observations indicated that the casing damage mechanisms are mainly buckling, diameter reduction and fracturing. From casing damage statistical results, it was found that casing buckling is the primary reason of casing damages. It was also discovered that the location of the most casing damage was within the zone where unconsolidated oil-bearing layer and poor cementing job exist. The explanation of casing failures in this case is that the casing loses its lateral constrains around these location, resulting in non-uniform pressures to be applied around the casing causing the collapsing in the form of buckling and shear failure.

2. Study area

Figure 1. A general map representing the location of Iranian oil and gas fields [7].

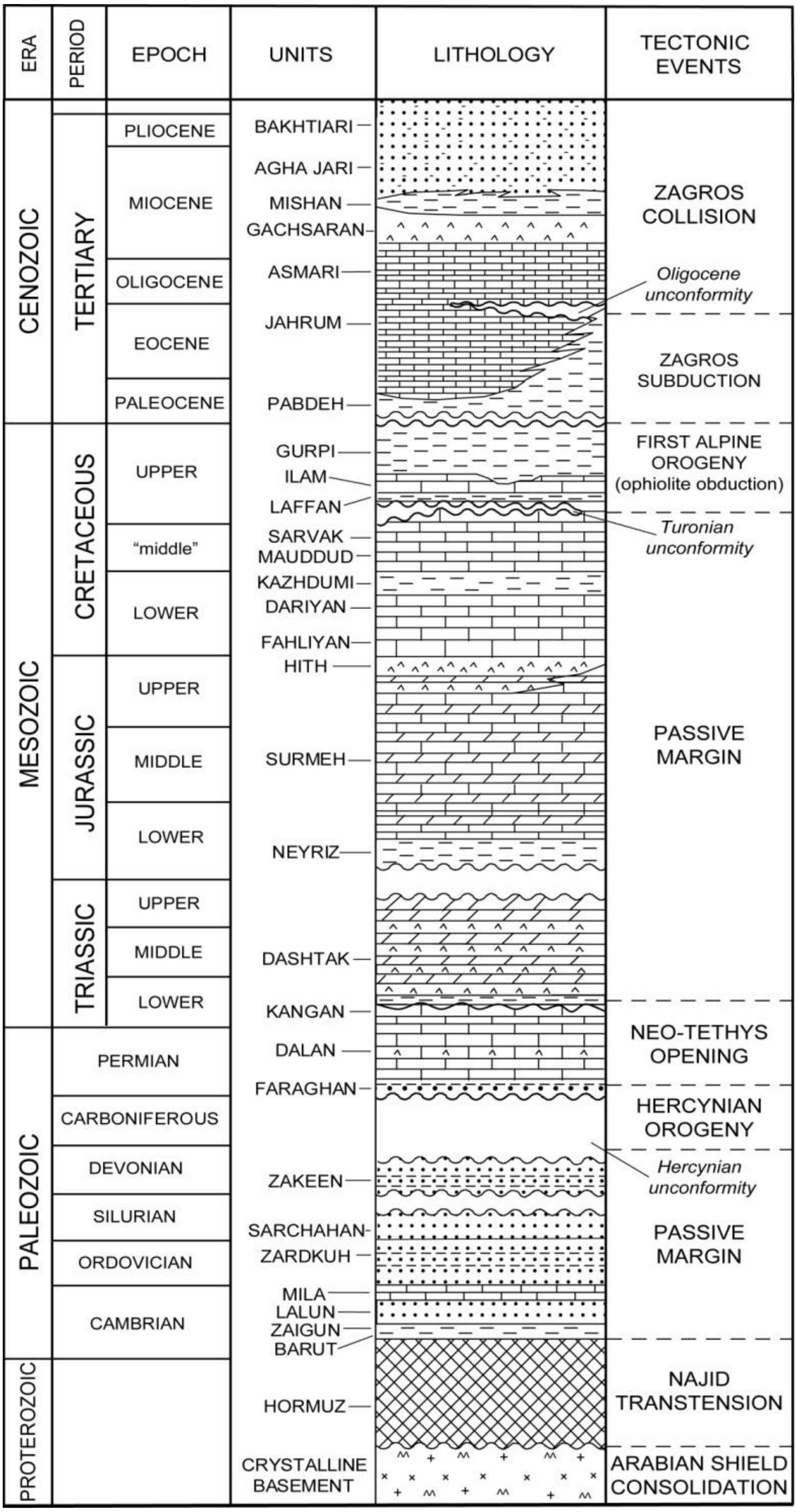

Figure 2. Stratigraphy of the Persian Gulf's formations [7].

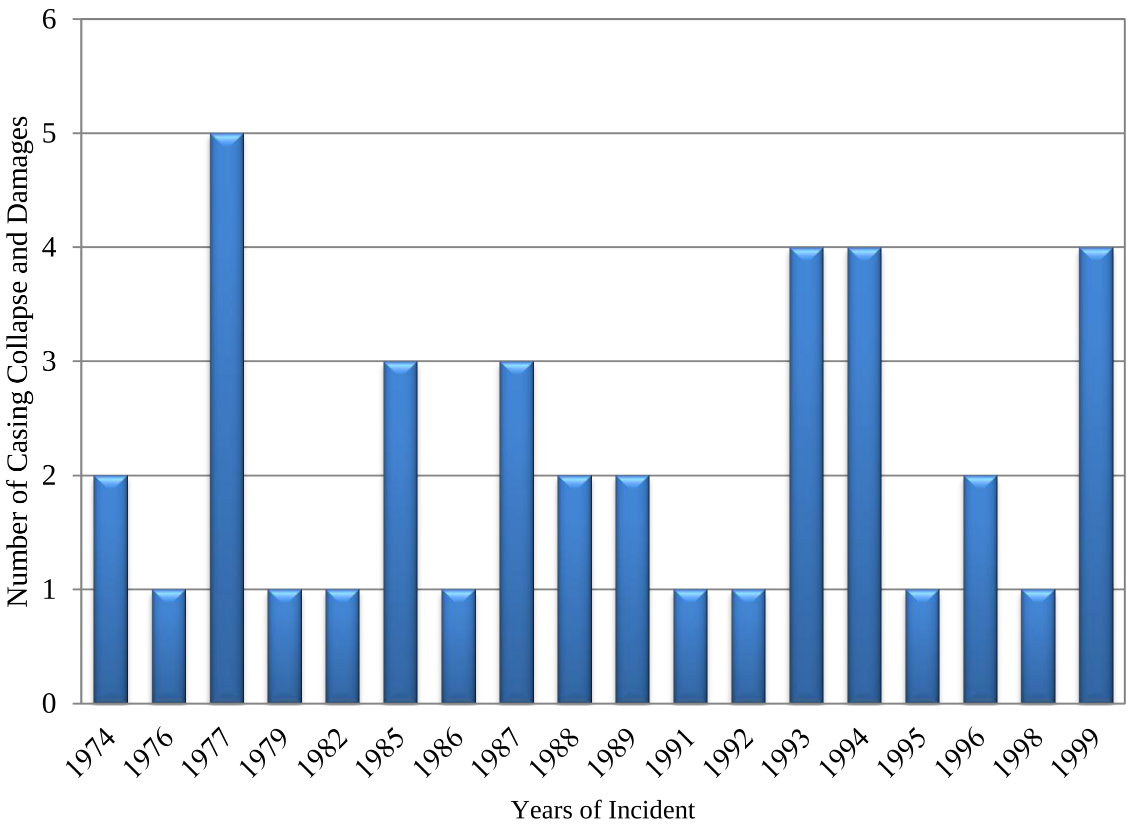

Figure 3. Casing collapse and damages incidents during the history of the field [2].

3. Finite Element Analysis (FEA)

Finite element Analysis (FEA) is usually used in geometrically or physically complex system where simple mathematical calculations are not able to provide sophisticated results. Discretization of the model into smaller parts known as elements enables the FEA to calculate the physical distortion and stress variations under different applied loads. Being a linear or non-linear material, mechanical properties including Young's modulus, Poisson's ratio and yield stress are assigned to each element, allowing the analysis to determine when modeling is undergone plastic deformations. To reach reliable results, continuous functions used to describe the complex shape of the model are replaced by approximate but effective function at specific points on the element called nodes. During the analysis, displacement is calculated first, strain is computed later and stress is finally evaluated by the use of Hook’s stress-strain relationship. Thus FEA would be able to provide approximate solutions for many engineering related applications where finding an exact integrated solution is barely possible [4].

In this section, numerical analyses is used to evaluate the interaction of casing, cementation and formations in order to find out what might be the possible reasons of casing damage in the field. This numerical analysis is done using ABAQUS software where finite element modeling is used to simulate casing damage condition.

3.1. Model assumptions and geometry

It is important to note that any kinds of problems considered to be solved using numerical analysis requires many simplifications as otherwise proper solution may never be found [8]. For the purposes of this study, FE model was defined as a two-dimensional model by considering the following assumptions [6]:

- The body forces does not vary in the direction of the body thickness.
- The applied boundary forces do not have any axial components and the forces are uniformly distributed across the thickness of the model.
- Loads may not be applied across the planes where top and bottom surfaces are bounded to each other.

In the FE model, subsurface layers were assumed to be homogeneous and modeled using a generalized plasticity model capable of simulating pressure dependency of rocks behavior. Linear and nonlinear shape functions were used in the discretization of the displacement and pore pressure field. The reduced integration of Pore Fluid/Stress type element and Drucker-Prager failure criterion with hardening was used for modeling of the formation. The direct Full-Newton solution was the techniques considered for the modeling purpose. In addition, the ABAQUS program provides a large deformation formulation allowing the simulation of significant displacements. Most importantly, the open environment of the software makes it possible for new material models to be involved in modeling. The reference 2D model used to investigate the effect of poor cementation on the casing collapse was initially built in ABAQUS software and shown in Figure 4.

Shown in Figure 4, formation is represented by maroon while the casing and cement sheath are shown in green and white colors, respectively.

The appropriate stresses corresponding to the boundary conditions of the model were estimated from a log based analysis, as shown in the last track of Figure 5. The size of the total model was much bigger than the wellbore size to accurately represent the effects of far field conditions on the region of wellbore [10]. The casing, cement and formation elements were modeled under plane strain conditions and formation elements contained an additional degree of freedom to accommodate the pore pressure effect in the model.

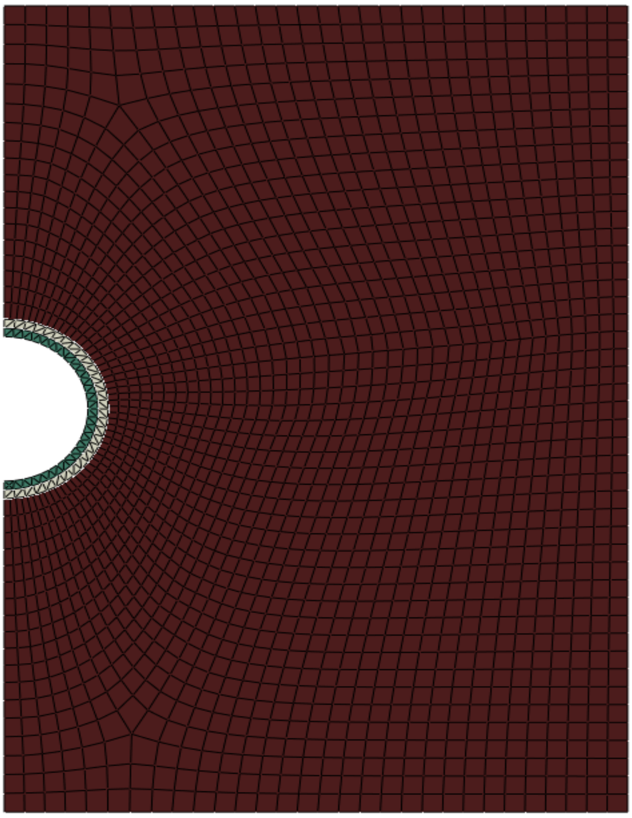

Figure 4. 2-D model built based on assumption of current study.

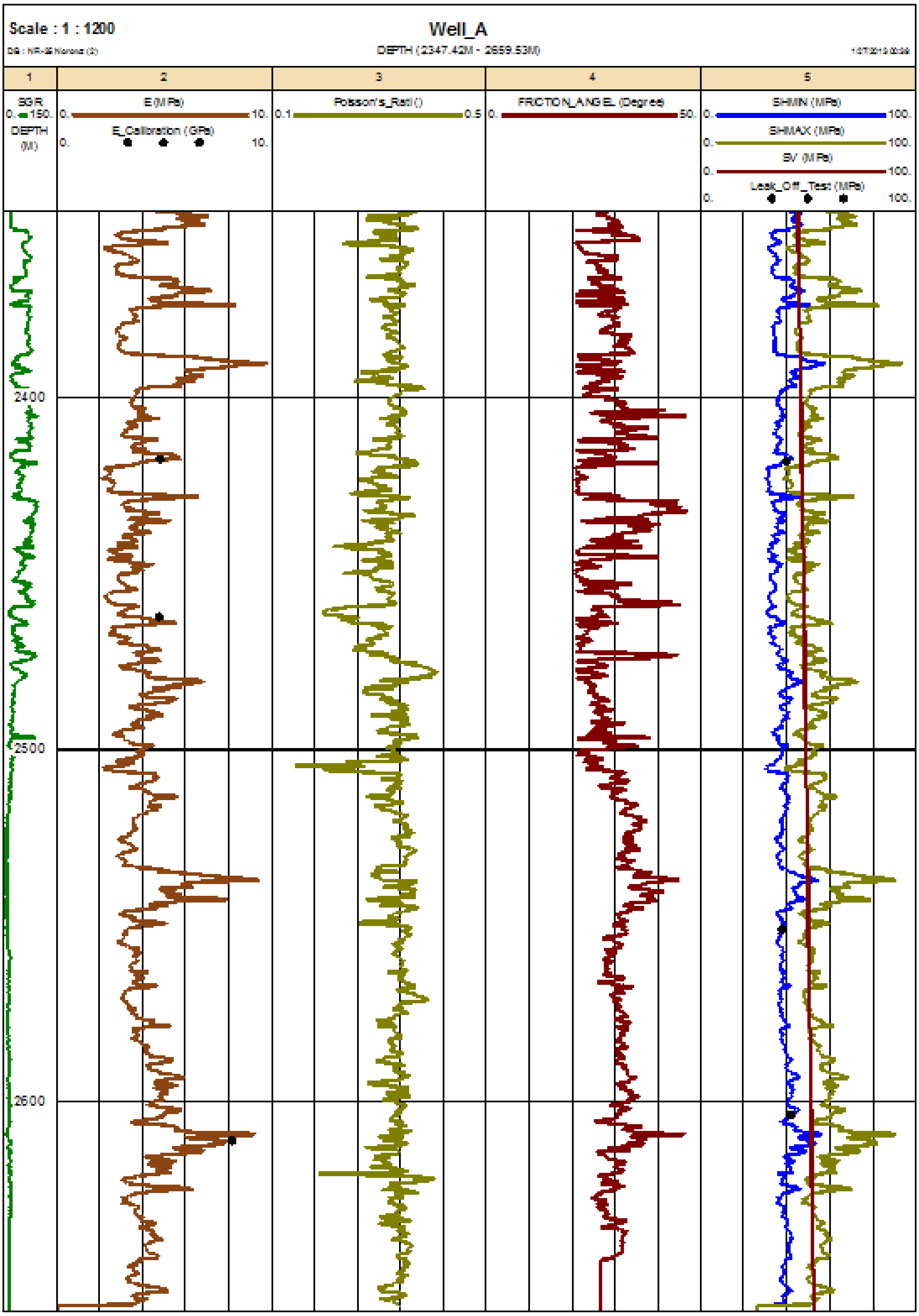

Figure 5. Formation elastic properties and magnitude of in-situ stresses estimated from log based analysis.

3.2. Material properties and boundary conditions

Formation mechanical properties, magnitude of pore pressure and in-situ stresses were estimated through a well-known log based analysis as shown in Figure 5. In this Figure, first track gives gamma ray log while the second track shows Young's modulus log calibrated against core samples. In the third and fourth tracks Poisson's ratio and friction angle logs are respectively depicted. In the last track, in-situ stresses obtained through log based analysis are presented and calibrated against Leak-off tests data.

Showing in Figure 5, Young's modulus and Poisson's ratio of the formation can be assumed to be 8GPa and 0.33, respectively at the interval where numerical analysis is done. The friction angle of the formation is 30 degree in the same depth and minimum and maximum horizontal are approximately 40MPa and 70MPa, respectively.

3.3. Casing, cement and drilling fluid properties

The casing was modeled with a uniform and circular geometry where the diameter to thickness ratio was considered to be 1/20. It was assumed that the wellbore was drilled with a 36 inch drill bit and cased with a 30 inch casing (i.e. conductor pipe). The maximum yield strength, Young's modulus and Poisson's ratio of casing were considered to be 375MPa, 200 GPa and 0.26 respectively.

It was generally known that when the principal stress components are compressive, the response of the cement is elastic-plastic [9]. Thus elastic-plastic material behavior was defined for the cement. In addition, the mechanical properties of the cement affect the magnitude of the stresses generated in the casing and as a result, the cement was modeled using the well-known Mohr-Coulomb criterion. Characteristics of the cement sheath are summarized in Table 1.

Table1. Material characteristics of the cement used in this study.

Elastic Properties	Young's Modulus (GPa)	Poisson's ratio	Friction Angel (Degree)
Cement	8.5	0.32	20

The formation fluid was assumed to be single phase (i.e., water) for FE modeling. The initial pore pressure of the model was considered to be 40MPa according to what has been obtained through geomechanical analysis and drilling reports. The density of drilling fluid used to drill this well across the reservoir section was $1.79 gr/cm^3$. Thus, the pressure equivalent to this density was applied on the internal side of the casing.

3.4. Finite element modeling

In this paper, interactions between casing, cementing sheath and surrounding formation were numerically simulated using general purpose finite-element software ABAQUS [11]. The model considers the plane strain condition and assumes that there is no heterogeneity in the formation.

In the developed model, the effect of drilling fluid inside the casing (i.e., internal pressure) on the mechanical strength of the casing was taken into account. It was assumed that there is a good bond between cement and casing and a contact interaction was considered between the cement and formation. The interaction was modified so that casing, cement and formation surfaces could not interfere with each other but they are allowed to deform. The casing and cement were also considered to be perfectly bonded. Thus, a frictionless contact was assumed between casing and cementing sheath whereas the interaction of cementing and formation was considered to be cohesive with small sliding.

To analyze and simulate the effect of good cementing job, the casing was modeled to be an elastic/perfectly plastic material. To prevent possible artificial locking in the calculation of stiffness matrices, a reduced integration technique was employed in the simulation [11]. Since the post-buckling shape of the casing is symmetry, half of the model was analyzed. To model the casing, 3-node linear plane stress triangle (i.e. type CPS3) was used for both casing ad cement whereas 3-node plane strain quadrilateral, bilinear displacement, bilinear pore pressure (type CPE3P) were respectively used to simulate the cementing sheath and surrounding medium. This dimension for the model seemed to be suitable for the surrounding medium since simulations of various model dimensions indicated a minor effect of larger domain and finer mesh on the accuracy of the modeling.

In order to improve the accuracy and efficiency of numerical simulation, a small element size was used in near wellbore and sparser mesh was used in the distal region of the wellbore. The heat transfer term was coupled to hydraulic and mechanical deformation terms using one-way coupling. The details of modeling procedure including its governing equations can be found in

the literature [12, 13].
In the next section, hydraulic-mechanical analyses and vonMises failure criterion used in modeling are presented shortly.

3.5. Hydraulic-mechanical analysis

Description and mathematical equations of mechanisms involved in the modeling of current study are presented below but more details can be found in ABAQUS User`s Manual [10]. The hydraulic and mechanical deformation terms are fully coupled in the ABAQUS software. The coupling is based on the equilibrium, constitutive and mass conservation equations described using effective stress theory explained below.

3.5.1. Equilibrium

Equilibrium for the hydraulic-mechanical analysis can be defined using the principle of virtual work for a given volume as follow:

$$\int_V \sigma : \delta\varepsilon dV = \int_S t.\delta v dS + \int_V f.\delta v dV \tag{1}$$

where v is the virtual velocity field, $\delta\varepsilon$ is the virtual rate of deformation, t is surface traction per unit area, and f is body forces per unit volume. The effective stress Equation under this condition is expressed as:

$$\bar{\sigma} = \sigma + U_w I \tag{2}$$

where I is the unitary matrix.

3.5.2. Constitutive equations

The constitutive Equation for the solid material is defined as:

$$d\sigma = H : d\varepsilon + a \tag{3}$$

where H is the material stiffness and a is strain independent contribution.

3.5.3. Mass conservation

A continuity Equation is used to relate the rate of increase in the liquid mass to the rate of mass of liquid as a function of time given below.

$$\frac{d}{dt}\left(\int_V \rho_w n dV\right) = -\int_S \rho_w n N V_w dS \tag{4}$$

and the liquid flow is described using Darcy's law:

$$S_r n V_w = -\hat{K}.\frac{\partial \phi}{\partial X} \tag{5}$$

3.6. VonMises failure criteria

By having knowledge about material properties, their geometries and loadings condition, stress redistribution can be calculated using numerical or analytical analysis. These stresses are then used to evaluate the integrity of a structure. For ductile materials such as casing, experimental studies revealed that acceptable agreement exists between experimentally determined yield stresses and the vonMises failure criterion. Thus this criterion (i.e. also known as minimum distortion energy theory) is widely used for ductile materials. In the vonMises criterion, failure is assumed to occur when combination of the three principal stresses exceeds the yield strength of the material as presented in Eq. (6).

$$\sigma_{vonMises} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}} \tag{6}$$

3.7. Modeling steps

The modeling was done through the following steps:

3.7.1. Model equilibrium

The model was brought to equilibrium at the initial load step by applying initial effective stresses, temperature and pore pressure and fixing displacements along the far field boundaries. It was assumed that stresses at the far field are constant throughout the modeling and initial displacements is zero before drilling. This was really important since the casing and cement elements must be deformed only as a result of loadings caused by drilling operation.

3.7.2. Drilling

To simulate the drilling operation, a half circle of the formation was removed causing the changes in initial state of stresses achieved through the equilibrium step. This removal eliminates the forces applied by this volume on the formation. This force release should be replaced by the pressure of drilling mud to reach the equilibrium during the drilling. If the pressure applied by drilling fluid is not quite enough to resists against the pressure of the formations, it is hard to achieve the equilibrium.

3.7.3. Running the casing and cementing

In this study, it was assumed that casing was run and cemented immediately after drilling and hence, after adding cement and casing elements, a force equal to the hydrostatic pressure of the mud was applied on the inner surface of the casing. The contact interaction between cement and casing was then considered for revealing how these two elements may react as a result of applying force. Interaction between cement and formation surface was also activated immediately after running the casing and doing the cementation sheath. These interaction enable us to monitor the reactions between the formations, cement and casing.

4. Results and discussions

4.1. Model 1

Considering the steps taken above, two models were simulated to compare the effects of good and bad cementing job on casing damage. All of the properties of the FE models were the same and assigned according to the procedures described in the previous sections. In the first model, perfect cementing without any voids was considered between the casing and formations. The aim of this model was to show how a good cementing sheath can protect the casing against excessive loads induced by the formation. Figure 6 shows vonMises stress distribution on the casing and cementing sheath.

As shown in this Figure, up to 49MPa stress was distributed around the casing that may cause the casing to damage. However, perfect bond between the casing and cement causes the cement to absorb all the stresses induced by the formation and prevent the casing to be damaged (See Figure 7). As shown in Figure 7, due to excessive loads induced by the far-field stresses, the cement displaced up to 1cm but there is no significant displacement occurred in the casing. In terms of shear stress, although it is observed that shear stress has been distributed significantly around the casing reaching up to 1MPa, it is not big enough to cause the casing to be damaged. This is mainly because of the important role of the cement protecting the casing against excessive loads applied by the formation. Figure 8 shows the shear stress distributed through the FE models after applying far-field stress.

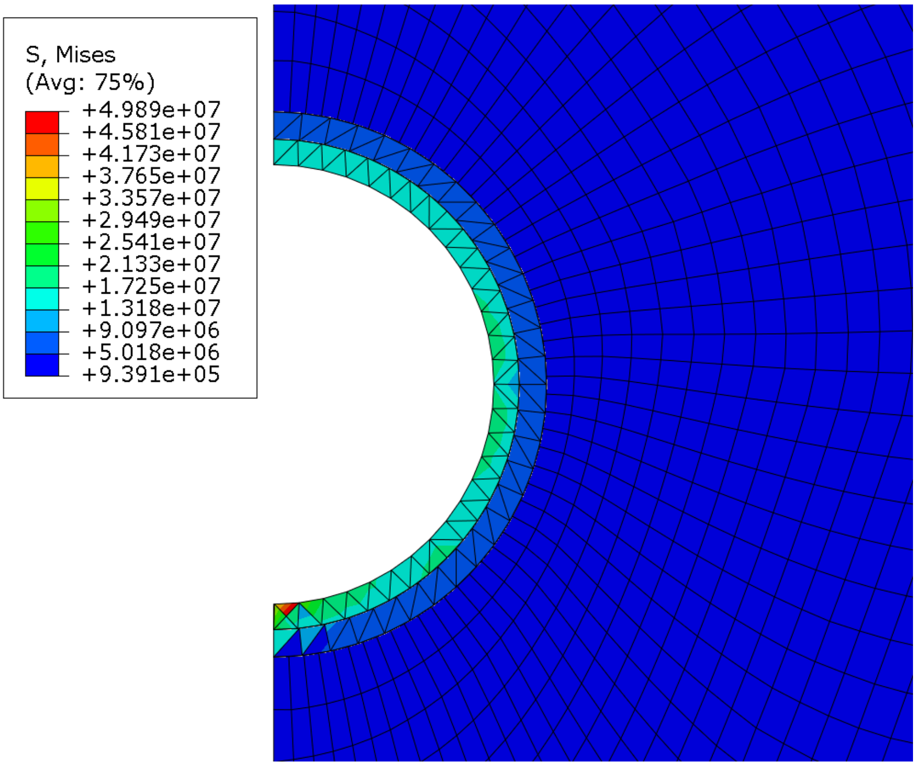

Figure 6. VonMises Stress distribution around the casing and cement sheath when a perfect bond exist between the casing, cement and surrounding formation.

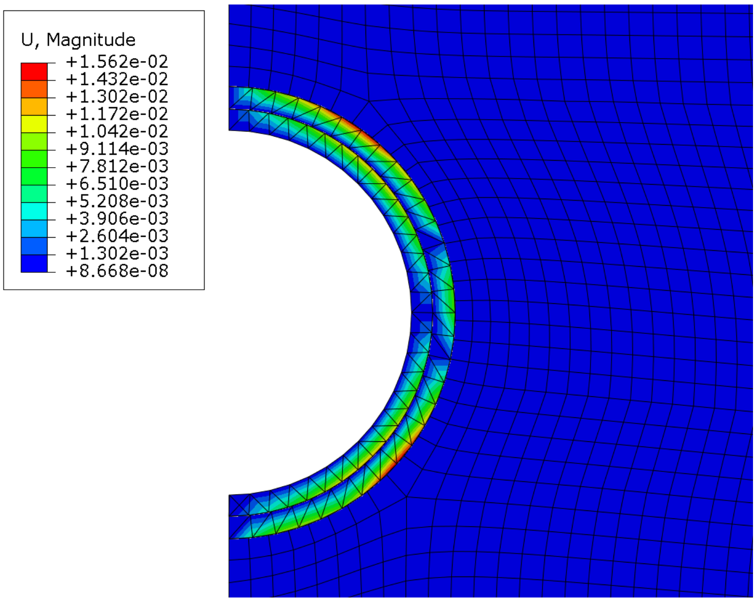

Figure 7. Displacement of the cement due to excessive loads induced by the formation.

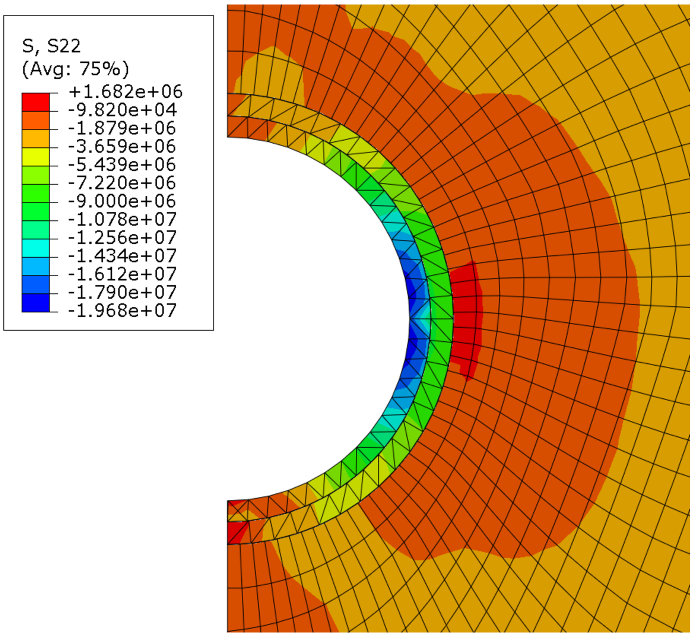

Figure 8. Shear stress distribution throughout the model after applying far-field stresses.

4.2. Model 2

The second case evaluated in this study considers the effect of voids in the cement sheath on stress distribution. Bad cementation and sand production during the life of the well are the main reasons of creation of voids. As a result, non-uniform stress may arise in the locations where casing is not supported by the cement causing the casing to be damaged.

In order to consider the effect of bad cementation job, it was assumed that the annulus is only partially filled due to a bad cement job. The void (channel) was considered in the model as a hole in the cement that was filled with fluid. It was also assumed that the boundary conditions of the void do not change during the simulation. This is due to the fact that material is porous and decrease in void size may push the fluid back into the formation [4].

The results of numerical modeling revealed that due to the weakness in cement sheath, vonMises stress increases significantly more than when a perfect cement sheath was considered (see Figure 9). As a result a non-uniform stress is created developing a bending in the casing at the edges of the void contact resulting in deformation of the casing in those regions.

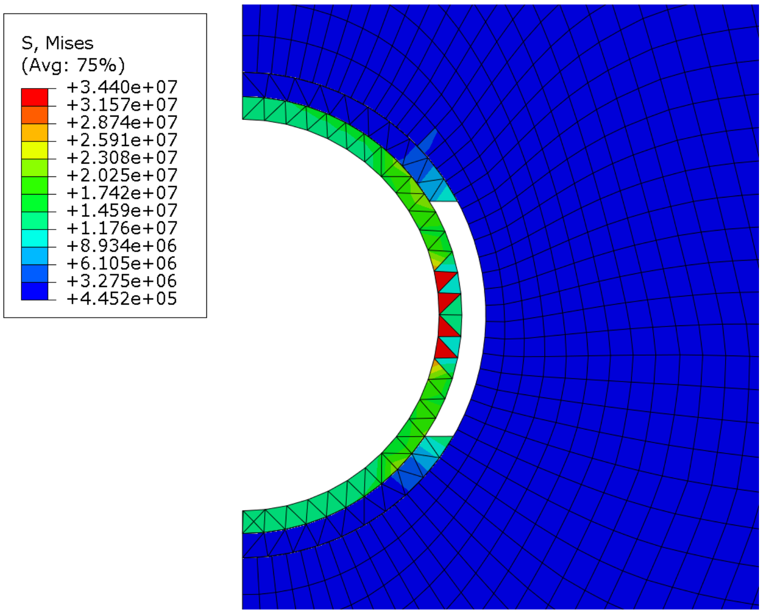

Figure 9. VonMises stress distribution case of poor cementing.

The results also indicated that due to the existence of the voids in cement, casing undergoes a considerable displacement and damage in the locations where cement sheath was removed (see Figure 10). This displacement was close to the value of displacement observed in cement in good cementing job condition. The difference is that the good cementing protects the casing against excessive load but the bad cementing operation will not be able to provide sufficient protection for the casing.

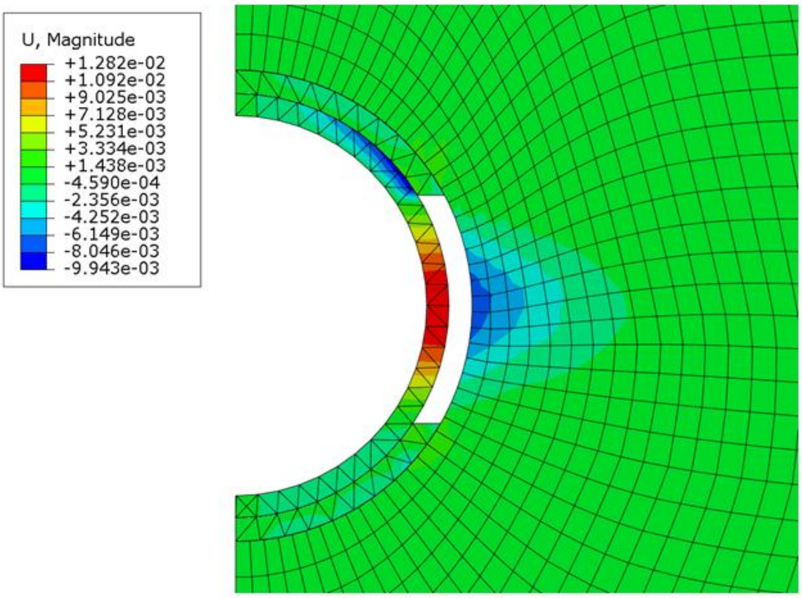

Figure 10. Displacement of the casing in the case of poor cementing job.

Looking at the variation of shear stress on the casing shown in Figure 11, one can conclude that because of the presence of the void in the cement, shear stress reached up to 1MPa which is slightly higher than the value experienced in the perfect cement sheath model. The only difference is that maximum shear stress has been distributed directly on the casing making the casing significantly damaged. In fact, this amount of shear stress is the main reason for casing collapse in those parts of the wells where poor cementing job exist.

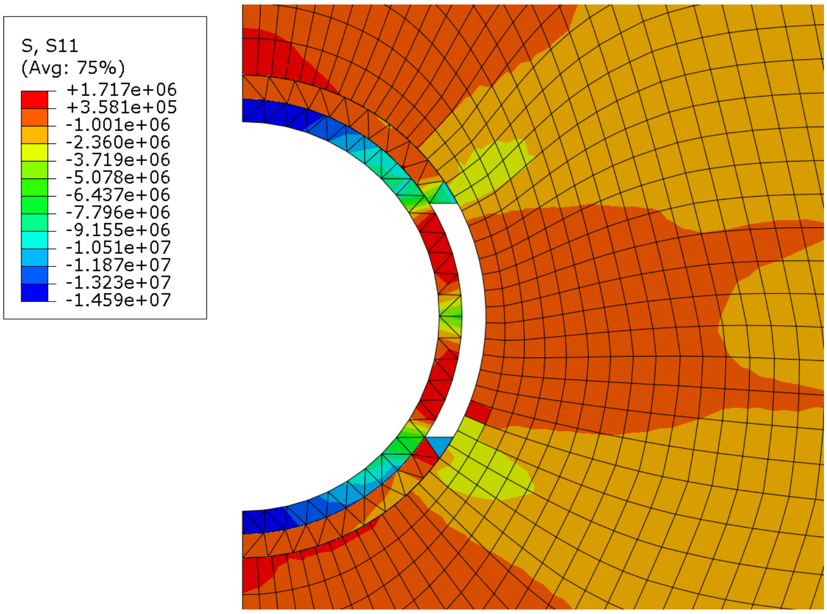

Figure 11. Shear stress distribution after considering voids in cement sheath.

5. Conclusions

To investigate the effect of uniform and non-uniform loading on casing due to the presence of void (channel) in the cement sheath behind the casing, two numerical models were developed. Under the assumed boundary conditions, mechanical parameters and in-situ stresses magnitudes used in the modeling, it was found that due to the presence of void in the cement and creation of non-uniform load, casing is deformed under the load significantly less than that of the obtained through modeling with perfect cementation. This showed the importance of good cement job during well completion programs. The results of this study also revealed that good cement should be used in the reservoir sections where high pore pressure and stress are applied on the casing, as otherwise the stress generated in the casing during subsequent operations may lead to casing damage. The developed numerical models were found to be very useful in understanding the behavior of casing under uniform and non-uniform stress conditions.

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شبیه‌سازی عددی تأثیر سیمان‌کاری ضعیف بر خرابی لوله جداری

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چکیده:

پارامترهای مختلفی بر خرابی لوله جداری تأثیر می‌گذارند که شناسایی دقیق آن‌ها از اهمیت بسیار برخوردار است. سیمان پرکننده فضای دیواره و لوله جداری، تأثیر مهمی بر مقاومت لوله جداری در مقابل بارهای وارده دارد. بسیاری از روابط تجربی، نقش این سیمان در مقاومت لوله جداری را نادیده گرفته و متعاقباً بار وارده بر لوله جداری را نیز یکنواخت در نظر می‌گیرند. در این مقاله، ضمن مدل‌سازی عددی، نشان داده می‌شود که چگونه یک سیمان‌کاری بد می‌تواند باعث تخریب لوله جداری بشود. به این منظور دو سیمان‌کاری متفاوت شبیه‌سازی‌شده و تأثیر آن‌ها بر مقاومت لوله جداری مورد بررسی قرار می‌گیرد. در هر دو نوع سیمان‌کاری، مقادیر مشابهی از تنش بر مرزهای خارجی مدل اعمال شده است. نتایج نشان می‌دهد که یک سیمان‌کاری خوب می‌تواند غلاف مناسبی در مقابل تنش‌های مماسی حاصل از تنش‌های دور ایجاد کرده و احتمال تخریب لوله جداری را کاهش دهد.

کلمات کلیدی: عملیات سیمان‌کاری، تخریب لوله جداری، آباکوس، اجزاء محدود، مناطق جنوبی ایران.