Research Article

Solid-geo-mechanical investigation of the effect of salt creep on casing stability using finite element method: a case study

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Abstract

The salt formation creeping can significantly affect the casing stability, because of the changes in mechanical and geomechanical parameters. The creeping of Gachsaran salty formation in the south part of Iran has influences on wells drilled in the region, which should be carefully considered in the casing design process. In this study, the finite element analysis technique was applied to study the alteration in mechanical/geomechanical parameters of a well in this formation. The accuracy of the methodology was validated by data available from the reduction in wellbore diameter of another well in the formation. Different scenarios were studied to analyze the effect of geomechanical parameters on stress, plastic strain, and casing diameter for a cased cemented well and a well completed with two casings. The effect of mechanical parameters on casing collapse was studied, where casing eccentricity, ovality, and slenderness ratio were also considered. Our simulation studies showed that casing stability in salty formations is strongly affected by geomechanical and pipe mechanical parameters. To reduce the severity of the casing collapse in salty formation, it is recommended to complete the well with two casings. Our study showed that, this arrangement reduces the plastic strain and the change in casing diameter significantly For a safe casing design, effect of mechanical parameters should be also considered. Effects of parameters such as ovality, eccentricity, and slenderness ratio are noticeable, for example, 2% ovality and 2% eccentricity in L-80 casing, lead to increase in the plastic strain from 0.112 to 0.31 and 0.3, and the overall diameter reduction from 0.455″ to 0.685″ and 0.535″, respectively.

Keywords Salt creep · Casing stability · Casing design · Solid mechanics · Geomechanics · Finite element method

1 Introduction

The salt dome is a possible structure of oil and gas reservoirs in different locations, such as Gulf of Mexico, North Sea, and North America [6, 21]. Because of ductility, domes may creep without creating any fracture. Once the salt formation has been penetrated by drilled wells, the creep deformation initiates [20]. Different oil reservoirs in the south of Iran, such as Maroon, are located below salt domes, such as Gachsaran formation. In these reservoirs, the creep behavior exerts the external pressure on

the drilled wells. Hence, for a successful casing design, the creep mechanism should be considered to avoid possible collapse, as a result of the excess pressure. Also, a study on Gachsaran formation presents an approach based on damage mechanics to determine the strain rate induced at different stages of creep. This study indicates that the viscoelastic behavior is changed under the influence of pressure and temperature of the wellbore. [8].

Cheatham and McEver [4] conducted experimental studies to analyze the casing behavior subjected to salt loading. They observed that, under the non-uniform

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loading (NUL), failure first occurs in cementing, however, if the well is appropriately cemented, the casing will be subjected to the uniform overburden pressure loading. Kuanhai et al. [9] analyzed the effect of axial length on the collapse of casing under non-uniform load in both macro and micro scales. The results obtained indicated that the yield load and instability load (bearing capacity) of the casings increased with increase in the axial length. Rodriguez et al. [15] modeled the casing and cement responses under loading by the finite element analysis. They stated that in the cemented wells, the casing resistance to the collapse is higher. Lin et al. [11] conducted an experimental/modeling study to analyze the casing collapse under NUL. They declared that the magnitude of external loading and degree of NUL are the essential parameters to be considered for an accurate casing design. Berger et al. [2] applied a finite element model to analyze the parameters affecting the casing collapse. They found that the accurate estimation of eccentricity, voids, cement channels, and pore pressure decline are crucial to predict the collapse risk. According to research on the effect of the casing eccentricity on the integrity of the cement sheath, poorly cementing increases this effect seriously. Therefore the risk of cement failure is reduced by setting thick and centralized casing strings [12]. Salehabadi et al. [16] investigated the effect of eccentricity in the gas hydrate bearing sediments under uniform and non-uniform loadings by the finite element method. They found that as casing eccentricity increases, the higher magnitude of stress is generated in the casing, which may lead to the casing collapse. Casing ovality is more significant in the weak reservoir layers. The ovality due to pressure drop increases and raises the probability of failure of the casing in the reservoir [22]. A 3D geomechanical model was developed by Wang et al. [20] to predict the effect of wellbore pressure and temperature, formation stress, and rock/cement/casing properties, on the creeping behavior. De Simone et al. [5] provided an analytical solution to calculate stresses during different operations. Generally, mechanical properties of casing pipes are affected by the pipe material, geometry, and the possibility of corrosion [13]. In salty formations, these parameters are also affected by the deformation of lateral salt layers [14].

Recently, Tao et al. [19] investigated the influence of non-uniform in situ stress on the casing stress. The nonuniform in situ stress affects the casing damage prediction due to the extreme value of the stress on the casing inner wall. Casing collapse behavior by considering the formation creep was studied by Ghodusi et al. [7] using numerical methods. Their results showed that ovality and eccentricity may increase the possibility of the casing collapse. Wells drilled in Gachsaran formation are also influenced from creeping phenomena. Taheri et al. [18] conducted tri-axial creep experiments on Gachsaran salt formation samples under various temperature and differential stress and they showed that the halite rock of Gachsaran formation obeys the power law. For a comprehensive study on Gachsaran field, the simultaneous effect of the geomechanical and mechanical parameters on the casing collapse should be considered. Researchers have suggested a variety of methods, such as use of concentric cemented casings in casing design [17].

In this study, the effect of the creeping in Gachsaran salt formation, on a well in Maroon oilfield was studied., Casing collapses were periodically reported in this giant oil field. The finite element method has been applied to consider mechanical/geomechanical parameters, model the plastic behavior, and quantify transient deformations of the casing to achieve the a successful casing design. Casing internal diameter, arrangement of casing string, casing eccentricity, ovality, and D/t ratio were considered as mechanical parameters in our model to study the casing deformation in the Gachsaran formation.

2 Methodology

2.1 Geomechanical modeling

Gachsaran formation consists of marl, carbonate, anhydride, and salt layers. Because of the presence of salt and marl layers, Gachsaran formation is considered as a relatively plastic formation, which is naturally more deformable than the upper and lower adjoining layers. The presence of unstable salt and marl layers between the anhydrate layers increases the deformability and develops numerous folds. Presence of these small unstable folds leads to the slipping of salt and marl from high pressure regions to low pressure sections in the formation.

Drilling a well in a salty formation increases the instability. As a result, in early times after drilling, the salt formation creep occurs in the wellbore. The purpose of our modeling study is to recommend strategies for a successful casing under the creeping condition in Gachsaran formation,

In this work, Abaqous software is used to model the stress and strain in the formation/wellbore area by the finite elements method (FEM). The material properties, such as Young's modulus and Poisson's ratio, were set for each element. In all elements, the displacement and strain were initially calculated, and then, stress was computed by stress–strain relationship [7]. Elasto-plastic deformation model was used to consider the plastic deformation.. The model was confirmed and used to analyze the effect of different parameters on the casing design and cost.

Parameters of the well No. 360 in Maroon field are considered as inputs for modeling, as shown in Tables 1 and 2, respectively. A part of the well is within the cap rock, and the casing shoe is located at the depth of 3600 m of the formation. As the well is vertical and there is no curvature or pipe eccentricity, the uniform loading condition was assumed.

2.2 Pipe selection criterion

Pipes with the external diameter of 9.625″ and internal diameter of 8.535″ are commonly used in the Maroon field. The weight of the pipes is 53.5 lb/ft and collapse parameters are different based on the grade of the pipe as shown in Table 3.

In this well, because of the presence of hydrogen sulfide (H_2S) gas, some classes of casing, such as non-API V and N-grades, cannot be used. C pipe is also removed from our selections as it is more expensive compared to other similar grades [1]. The L-80 high-strength H_2S resistance casing is used in our simulations, which is also recommended for the similar cases [3]. The Young's modulus and Poisson ratio of the L-80 pipe are 220 GPa and 0.3, respectively.

The developed model was validated using the data of a nearby well in the same formation. To investigate the effect of geomechanical parameters on stress/plastic strain/casing diameter reduction, different scenarios, such as a cased cemented well and a well with two casings, were modeled. Also, the effects of casing eccentricity, ovality, and slenderness ratio on casing collapse were investigated. The main assumptions in the geomechanical modeling are as follows:

Table 1 Data of well no. 360 in the Maroon oilfield

General properties	
Well No.	360
Depth (m)	3600
Rock density (kg m^{-3})	2431
Mechanical properties	
Young's modulus (MPa)	55
Poisson's ratio	0.296
Friction angle (°)	45
Thermal properties	
Heat capacity $\left(\mathbf{J\ kg^{-1}\ K^{-1}}\right)$	979.06
Initial condition	
Temperature (°C)	120
In-situ pore pressure (Mpa)	71.35
In-situ maximum horizontal stress (MPa)	88.56
In-situ minimum horizontal stress (MPa)	79.37
Overburden pressure (MPa)	85.86
Mud weight (kg m^{-3})	2307

Table 2 Cement class G parameters

Young's modulus (GPa)	2
Poisson ratio	0.1
Density (kg m^{-3})	1842
Thermal conductivity $\left(\mathbf{Wm^{-1}\ K^{-1}}\right)$	1.385
Heat capacity $\left(\mathbf{J\ kg^{-1}\ K^{-1}}\right)$	1765.65

1. The well was drilled in an evaporating salty environment.
2. As the salt layer is thick (35.5 m), the modeling was done in two dimensions and in the strain plane mode.
3. The salt rock is homogeneous and isotropic, with negligible permeability and porosity, and with no faults.
4. The salt rock, under low differential stresses, behaves as a ductile formation which is able to tolerate the considerable deformation without any failure. Hence, the probability of existence of fractures and joint sets in the Gachsaran salt formation is very low.

Figure 1 shows the geometry of the model with finer grids close to the wellbore, to improve the accuracy of the analysis. To reduce the effects of the boundaries, their lengths are approximately set to be 30 times of the well radius. The rock density and properties of the salt layer are obtained from the well logging data. The dynamic elastic properties are converted to the static elastic data, using the following equations [23]:

$$v = 0.5\left(\left(\Delta ts/\Delta tc\right)^2 - 2\right)\Big/\left(\left(\Delta ts/\Delta tc\right)^2 - 1\right) \quad (1)$$

$$E = 1.34 * 10^{10} * (\rho_B/\Delta ts^2) * \left(3\Delta t_s^2 - 4\Delta t_c^2\right)\Big/\left(\Delta t_s^2 - \Delta t_c^2\right) \text{ (psi)} \quad (2)$$

$$G = E/2(1+v) = 1.34 * 10^{10}\left(\rho_B/\Delta ts^2\right) \text{ (psi)} \quad (3)$$

$$K_b = 1.34 * 10^{10}\left(1/\Delta t_c^2 - 4/3\Delta t_s^2\right) \text{ (psi)} \quad (4)$$

Table 3 Casing specifications used in the Maroon field

Pipe grade	Collapse pressure (Psi)	Burst pressure (Psi)
API L-80	6620	7930
API N-80	6620	7930
API C-95	7340	9410
API P-110	7950	10,900
Non-API V-150	8960	14,860
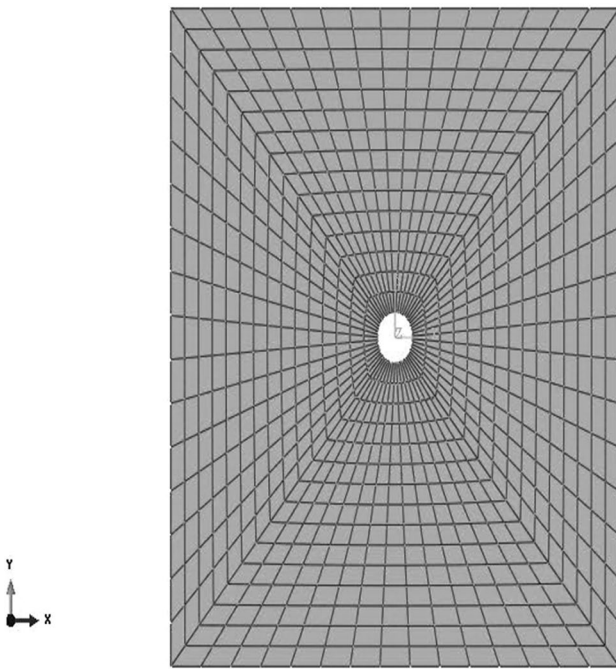
Fig. 1 Gridding structure of the open well in the model

located in the Gachsaran salty layer formation. Hence, the geomechanical behavior of these two wells are similar. The developed model was used to predict the plastic strain and wellbore diameter of the well No. 320, after 10 years of production under the creeping condition of the salt formation. The results are shown in Figs. 2 and 3. Figure 2 illustrates the variation of the plastic strain of the pipe in the well No. 320. The model prediction of the plastic strain after 10 years is equal to 0.106, which is very close to the value measured and reported by the operator in the field, i.e., 0.108. Figure 3 shows the pipe diameter variation modeled versus time for the well No. 320. After 10 years, the inner diameter size declines to 8.090 inches, which is very close to 8.088 inches which was measured and reported by the operator. Hence, with high level of reliability, the model prediction is in agreement with the field data, which confirms the validity of the model.
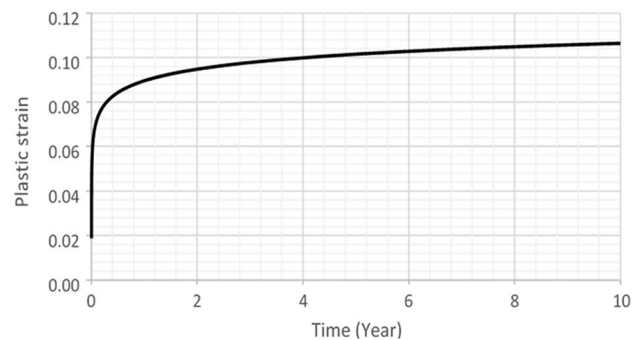
where v is Poisson's ratio, E is Young's modulus, G is shear modulus, K_b is bulk modulus, ρ_B is matrix density (g/cm^3), and Δt_s and Δt_c are shear and compressional transit time (μs/ft), respectively.

The number of grids is determined using the principle of linear independence. The number of grids in the network of casing, cement, and formation are set to be 1000, 1500, and 900 respectively. The number of grids in the of the pipe model is set to 400 to study the plastic behavior of the system. The shape of the elements is quad dominated, and the free meshing method is used. The type of grids in the salt formation is radial, and the size of grids is proportional to the distance from the wellbore.

As the model is 2D, there is no effect of salt creep in the vertical direction along the well. The external loadings cause considerable strains in the radial direction; therefore, in our model, the plane criterion was applied to model the effect of salt creep on the casing collapse.

3 Results and analysis of simulated cases

3.1 Validation of the geomechanical model

To validate the geomechanical model, the data of a similar well in the field (well No. 320) was used. This well was drilled in 2006. The size, grade, and weight of casings used in both wells, 320 and 360, are identical. Also, the depth of casing shoe of well 320 is 2801 m, which is

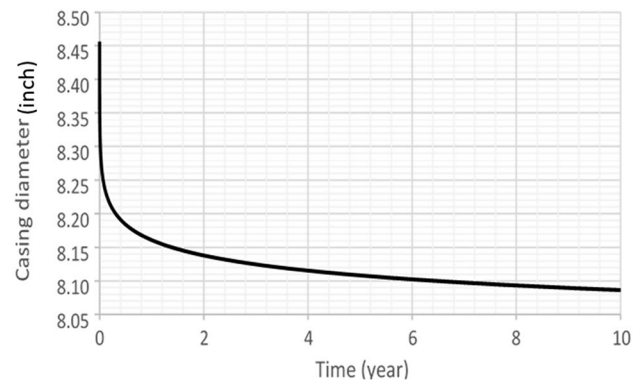**Fig. 2** Plastic strain versus time at well no. 320 in the Maroon oilfield

Fig. 3 Casing internal diameter versus time in well no. 320 in the Maroon oilfield

3.2 Effect of temperature on casing collapse under the salt creeping condition

The temperature is an important factor affecting the salt creeping rate. The temperature gradient in the Maroon oilfield is equal to 0.01°F/ft, so the reservoir temperature is about 120 °C. To study the effect of temperature on the creeping strain, three temperatures of 100, 120, and 140° C were considered in the modeling. As shown in Fig. 5, if the temperature increases, the strain of salt rock will increase. However, the change in the creep strain is not significant, which shows the low dependency of salt rock creeping on temperature for the well No. 360 (Fig. 4).

In salt rocks, because of the oil production, all parameters are time dependent. Hence, the transient analysis of forces applied on casing is critical to accurately predict the possibility of casing collapse. In the next section, different casing arrangements will be analyzed at the transient conditions.

3.3 Cemented cased well

In this type of completion, the well is cemented behind the casing. The effect of salt creep on casing stability was modeled and analyzed. In this simulation, the casing L-80, 9.625 inch, with specification shown in Table 3 was used. Due to the increase in the stress on the casing pipe by creeping, strain distribution around the wellbore will be high after 10 years. Figure 5 shows the contour of the creep strain distribution in Gachsaran salt formation at the wellbore and casing after 10 years. As shown in this figure, with the increase of the distance from the wellbore, the strain is reduced and the maximum changes occur near the wellbore, and the strain approaches zero at positions far away from the wellbore. Hence, the plastic strain and casing diameter alter versus time. Figure 6 shows the plastic strain on the casing which proves the
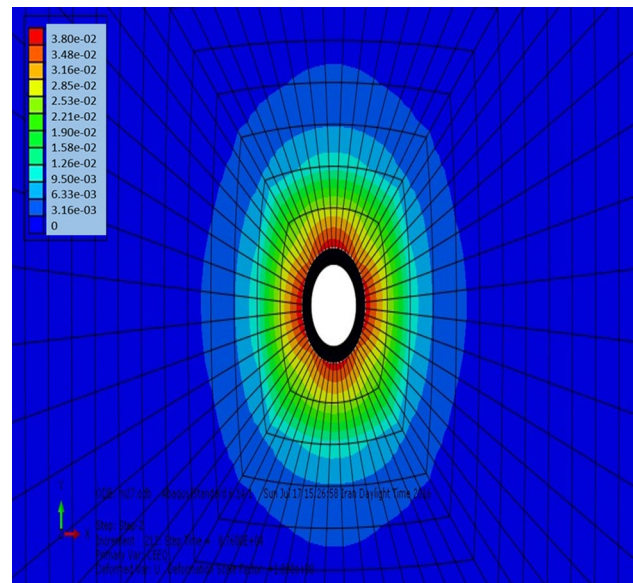

Fig. 5 Creep strain of Gachsaran salt formation at the wellbore and casing after 10 years

elasto-plastic behavior. The casing strain reached to 0.112 after 10 years. Figure 7 shows the casing diameter reduction by time. For the case of using only one casing in the well, the casing diameter reduction is about 0.45. As shown by red arrow on Figs. 6 and 7, the wellbore encounters great amount of alteration in diameter and plastic strain, only after a 28 days of running the casing. This phenomenon, which is the dominant mechanism in the casing stability, is because of the mechanical and geomechanical parameters of the formation. Hence, in the casing design for salty formations, both the geomechanical and solid mechanical parameters should be regarded.
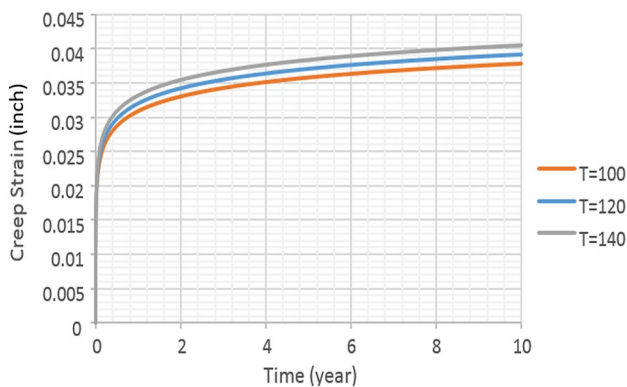

Fig. 4 Change in strain due to creeping at different temperatures in well no. 360
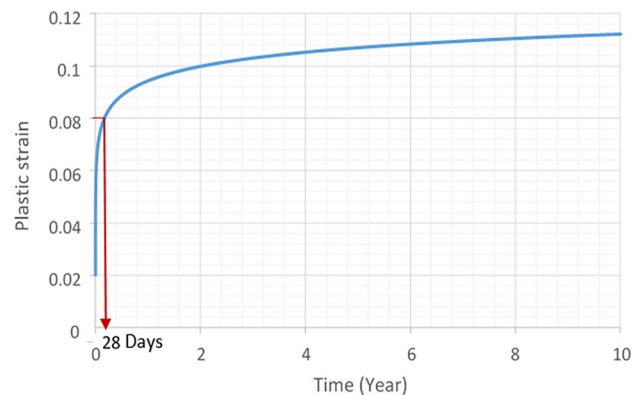

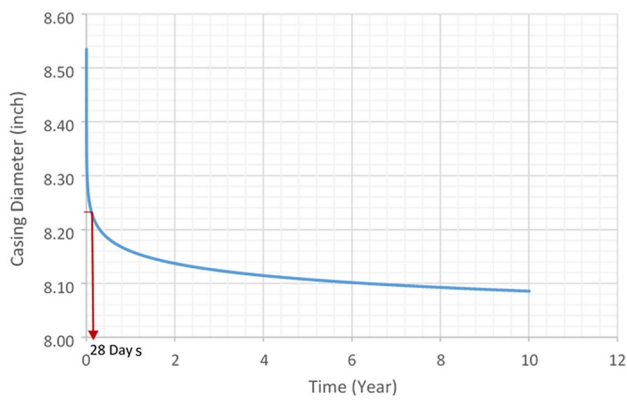**Fig. 6** Plastic strain versus time for well no. 360, as a result of creep

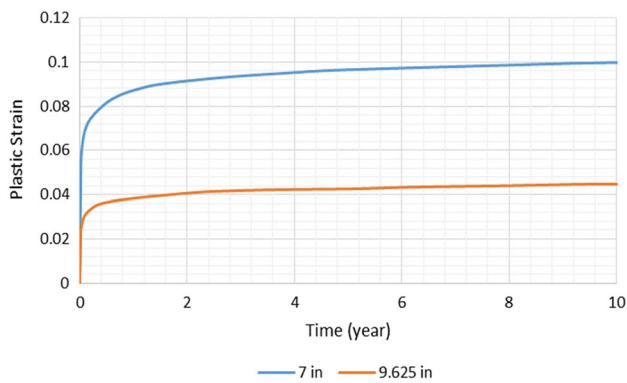**Fig. 7** Casing diameter versus time for well no. 360, as a result of creep

Fig. 8 Plastic strain in casing/liner pipes for the case of dual casing completion

Fig. 9 Changes in diameter of liner (inner casing) as a result of salt formation creep
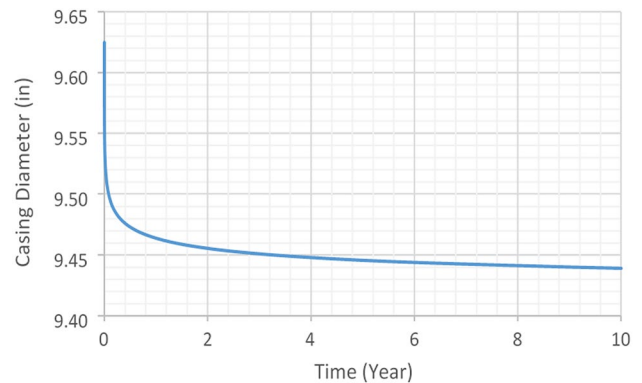
Fig. 10 Changes in diameter of casing as a result of salt formation creep

3.4 Dual casing well

One of the methods for controlling and stopping the rupture of casing in the salt formation is application of liners. To analyze the resistance of a casing/liner system, a 9.625 inch casing and a 7 inch liner were modeled. In the salt formation, the gap between the first casing and the well is not cemented to control the effects of the creeping mechanism. The creeping of the salt formation may enhance the possibility of casing collapse in Well No. 360. Hence, the dual casing design is modeled and investigated to improve the stability of the well. Stress and strain distribution were simulated and analyzed after 10 years of production. Figure 8 shows the variations of strain in both 7 and 9.625 inch pipes. Comparing Figs. 6 and 8 shows that the strain in 9.625 inch casing has been significantly reduced compared to the single casing completion.

Figures 9 and 10 show the diameter changes of the liner and the casing, which are equal to 0.26 inch for the liner and 0.185 inch for the casing after 10 years, confirming the higher stress on the liner. For the case of using only one
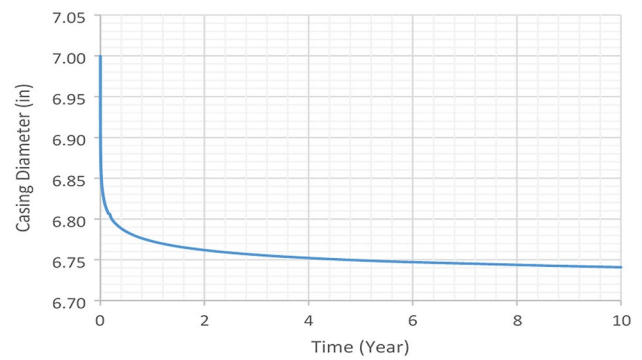
casing in the well, the casing dimeter reduction is about 0.45 inch, but in this case, this value is reduced to 0.185 inch, although the amount of plastic strain is not negligible as a result of the flaw in pipe constructions.

In the case of using two casings, if the collapse is only related to the salt creep, it will be hampered. In dual casing completion, the casing stability has been significantly improved and the influence of salt creep has been reduced. For a safe casing design, the effect of solid mechanical parameters should also be evaluated. Next section will show that to consider the geomechanical and solid mechanical parameters, and cost/operational aspects of different casing grades, using the double casing completion in the well is recommended.

3.5 Solid mechanics results

As mentioned in the previous section, the greatest change in the casing diameter of well No. 360, in the Maroon oilfield, occurs at initial times after running the casing. It indicates that the solid mechanics modeling of pipes is critical to predict the wellbore behavior. In this study, to
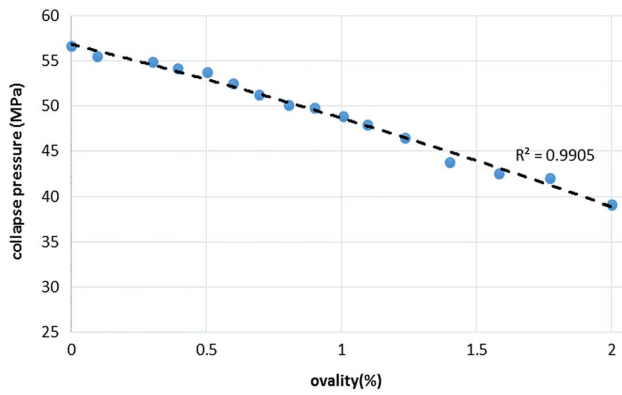
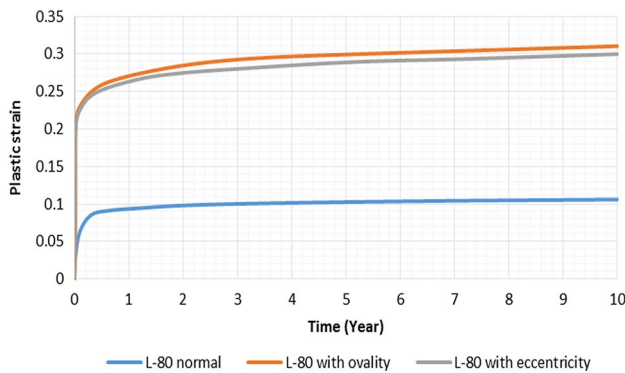**Fig. 11** Effect of ovality on casing collapse pressure

Fig. 12 Plastic strain due to 2% ovality and 2% eccentricity

Fig. 13 Diameter reduction due to 2% ovality and 2% eccentricity

Fig. 14 Effect of eccentricity on casing collapse pressure

improve the casing design, solid mechanical parameters such as eccentricity, ovality, and slenderness were investigated to study the possibility of casing collapse during the cementing.

As shown in Fig. 11, the sensitivity analysis was done to study the effect of the ovality on collapse pressure. As ovality increases, the collapse pressure decreases. This reduction is about 30.37% of the initial value, which is a considerable value.

If there is only 2% ovality in the casing, the value of plastic strain in casing is significantly increased, and after 10 years, it reaches to 0.31, as modeled and shown in Fig. 12. This value is much greater than the circular pipe condition, where the plastic strain is 0.112. The same issue is observed for the diameter reduction. Figure 13 shows the diameter reduction for the casing with 2% ovality. At the early time, the casing diameter reduction is about 0.335 inch, which reaches to 0.685 inch after 10 years. In comparison to the single casing completion, the overall diameter reduction increases from 0.45 to 0.685 inch.

Another flaw, which may occur in the pipe construction, is eccentricity. Figure 14 represents the changes in the collapse pressure as a function of eccentricity. Increase in the
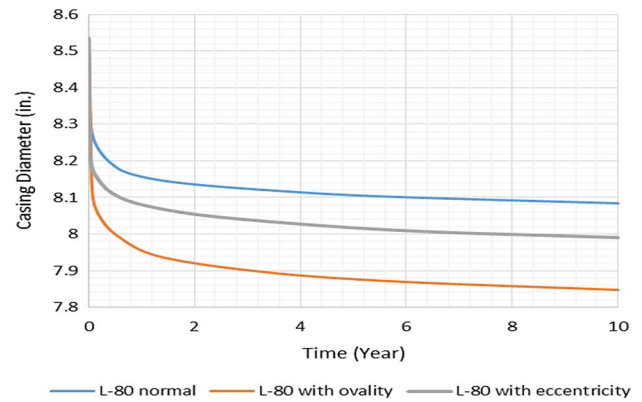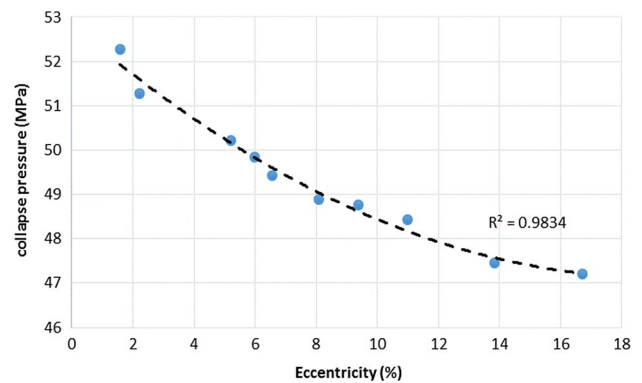
eccentricity leads to lower collapse pressure. The results of the simulations indicate that, any flaw construction in the pipe, decreases the collapse pressure. To investigate the effect of eccentricity on the casing collapse of well No. 360, the casing L-80 with 2% eccentricity was modeled.

Figure 12 shows the plastic strain of the casing. Obviously, increasing the casing eccentricity significantly leads to more plastic strain. Figure 13 shows the diameter reduction in pipe over time. In comparison to the single casing completion case, the casing diameter reduction has increased from 0.45 to 0.535 inch.

The effect of slenderness ratio, D/t, has been modeled, as shown in Fig. 15. If the ratio, D/t, increases, the collapse pressure decreases. Therefore, it is always possible to control the collapse pressure by adjusting the slenderness ratio. Hence, similar to ovality and eccentricity, this parameter also provokes the amount of strain in casing collapse, as a construction defect in the pipe.

So far, different research has been done using static and dynamic models. Although these methods were evaluated by lab and simulations, the accuracy of them in the field scale is low. Accurate modeling to reduce the severity of
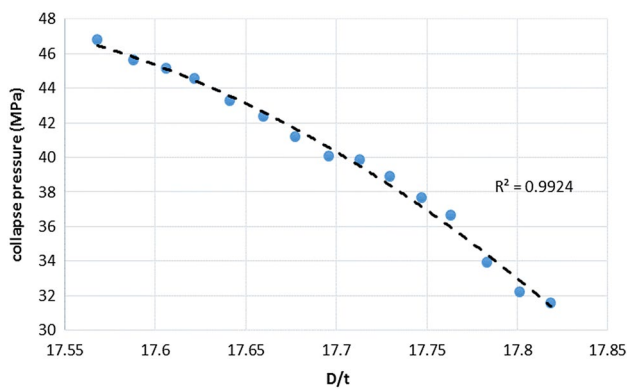
Fig. 15 Effect of slenderness ration on casing collapse pressure

the casing collapse in salty formation is critical. Otherwise, to repair the well, we have to set up the drilling rig again and put smaller size of the casing in the failure condition. In addition to the excessive cost of drilling, production will be reduced from a smaller hole.

Simplifications in mathematical and mechanical models for simulation are the two main reasons for the error modeling in the field scale. For example, incorrect assumptions in key parameters, incorrect boundary conditions, and the use of incorrect differential equations can cause deviations [24]. Considering finer grids close to the wellbore improves the accuracy of the analysis. In our work, a sensitivity analysis was conducted to consider all key parameters affecting the casing collapse. It was found that although the strain of salt rock increases at high temperature (Gholami et al. [8]), creeping for the well No. 360 has a low dependency on temperature.

Comprehensive investigation of key parameters and evaluation of the geomechanical model using real field data for improve the accuracy of our approach. Comparing the performance of the dual casing completion by the other cases in our results indicates that the casing stability is significantly improved and the influence of salt creep on the casing stability has been reduced by using two casings. This method is also confirmed by another study on casing deformation in a tectonic setting [10].

4 Conclusions

- In studying the casing design, not only the geomechanical parameters should be evaluated, but also the pipe related solid mechanics factors should be considered. This point is more severe in the presence of salt creeping mechanism, because it can strongly accelerate the casing diameter reduction. A comprehensive simulation study was presented to predict the casing stabil-

ity of a well drilled in a salty formation. Approaches to prevent the casing collapse were also recommended.

- Our results show that by using a single casing completion, the casing internal diameter reduces from 8.535″ to 8.080″ (0.455″ reduction), and plastic strain after 10 years increase to 0.112, which are severe and may lead to the casing collapse. By using the dual casing completion system in the salty formation, the casing instability was significantly reduced. For example, the alteration in casing diameter reduced from 0.455″ to 0.185″ which shows the higher stability of the casing. The same behavior was observed by modeling the plastic strain. Switching from the single casing completion to the dual casing reduces the plastic strain in the system.
- The effect of alteration in the temperature on the creeping mechanism in the salty formation is small and negligible.
- Increasing the solid mechanical parameters, including casing eccentricity, casing ovality, and D/t ratio significantly reduces the collapse pressure, increases the plastic stress, and reduces the wellbore diameter. For example for a L-80 grade casing with 2% ovality and 2% eccentricity, the plastic strain increases from 0.112 to 0.31 and 0.3, respectively. Also the overall diameter reduction increases from 0.455″ to 0.685″ and 0.535″ in, respectively.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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