Three-dimensional geomechanical model of creep behavior on wellbore casing in the composite salt–gypsum formation

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Abstract. According to statistics, a certain proportion of the world’s oil and gas resources are stored under the salt rock in the sedimentary basin. These reservoirs are located in formations called “pre-salts,” which are below the salt formations. They are widely found in the Sichuan, Tarim, and Changqing oilfields and in West Africa, offshore Brazil, the Gulf of Mexico, and the North Sea. The salt–gypsum layer exhibits a rheological property, which has a significant influence on casing damage. Creep deformation of the composite salt–gypsum formation occurs over time. Moreover, it applies excess stress on the wellbore casing, which can lead to casing damage. In this study, triaxial experiments are conducted on samples of salt–gypsum composite rock, and a power-law creep constitutive model is created. In the experiment, room temperature and humidity conditions are applied. Three types of loading, including axial and confining pressures, are separately applied on the samples, including the confining pressure (5 MPa) and the axial pressures (20, 25, and 30 MPa). From the experimental results, the relation between creep strain and time can be obtained, and a power-law creep model can be matched as the constitutive equation, which indicates that the strain rate is dependent on differential stress and temperature. The Abaqus finite element method software is used for establishing a 3D geomechanical model with formation stress and wellbore pressure to evaluate the life expectancy of wellbore casing. According to the triaxial rock experiment in the laboratory and according to field data, the mechanical parameters of the salt–gypsum formation and the parameters of the pre-salt reservoir are obtained, respectively. The results demonstrate that the von-Mises stress on the wellbore casing in the salt–gypsum layer increases during the production period. Meanwhile, the creep deformation of the formation also increases and applies extra loading on the casing, which is prone to exceed the strength and damage. Moreover, in this research, the discontinuous stress and deformation at the interface of the composite salt–gypsum formation, on which few researchers have studied until now, can be quantitatively described. The results indicate that the stress on the wellbore casing in the pre-salt layer is different, that is, the stress abruptly changes at the interface between pre-salt and salt–gypsum formation. The results also show the discontinuous creep deformation at the interface and that the casing is prone to shear collapse. Considering the sudden change in the stress at the interface of the formation is important. These results can be utilized to establish a casing design and for the analysis of wellbore integrity. For instance, the composite salt–gypsum layer should pass through the design of the double-layer casing and enable the thick-walled casing to increase its strength.
1. Introduction
Salt–gypsum layer refers to the stratum with salt or gypsum as the main component. In the petroleum industry, the salt–gypsum layer is generally referred to as the formation whose main component is sodium chloride or other water-soluble inorganic salts, such as potassium chloride, magnesium chloride, calcium chloride, gypsum, or thenardite as salt-containing gypsum formation. The salt rock found in the sedimentary basin is the best-quality cap rock, under which 80% to 90% of the world’s oil and gas resources are buried. Thus, the salt–gypsum layer is not only the focus of the world’s oil industry but also the focus of the development of China’s oil and gas resources.

In China, the salt–gypsum layer is widely distributed. It is located in Jianghan Oilfield, Zhongyuan Oilfield, Qinghai Oilfield, Sichuan Basin, North China Basin, Xinjiang Oilfield, Changqing Oilfield, Shengli Oilfield, Tuha Oilfield, Jiangsu Oilfield, Tarim Basin, Bohai Sea, etc. However, due to the different deposition environments and conditions in different regions, the burial depth and thickness of different salt–gypsum layers and the composition of the salt–gypsum layers are also significantly different. The depth of some salt–gypsum layers from the surface is more than 5,000 m. Moreover, the thickness of the single layer is from a few centimeters to more than 80 m, and the total thickness can be from tens of meters to more than 2,000 m, which greatly varies (Li et al., 2019).

![Distribution map of the global salt basin (Warren, 2010)](image)

**Figure 1.** Distribution map of the global salt basin (Warren, 2010)

Since the 1980s, numerous scholars at home and abroad have been studying the mechanical properties of salt rocks. The salt rock strength and deformation theory have been established through uniaxial and triaxial experiments (Cristescu & Hunsche, 1998; Hunsche & Hample, 1999; Yang et al., 2002; Liu et al., 2006a; Liu et al., 2006b; Ren et al., 2011; Li et al., 2014; Zhang et al., 2014; Liu et al., 2017; Fan et al., 2019). By conducting the triaxial experiment, it was found that when the confining pressure of the experiment was different, the salt rock sample exhibited different characteristics. At the same time, the loading strain rate also affected the salt rock strength. Through numerous laboratory experiments and a theoretical analysis, Huang and Deng (2000) studied the changes in the rheological coefficient of mudstone and salt rock with stress, temperature, and water content. They also established the correlation between the rheological coefficient and the different factors. The research provided important basic data for the deformation, shrinkage rules, and casing external load calculation. Liang and Zhao (2004) conducted a uniaxial compression experiment and used anhydrous glauberite salt rock as a sample. Through the experiments, it was found that during the uniaxial compression experiment of anhydrous glauberite, the failure mode was mainly the ductile failure, and it exhibited different deformation characteristics from ordinary rock samples. According to the experimental results, Liang and Zhao (2004) formulated the strength curve equation in the form of the Mohr–Coulomb criterion. Liu et al. (2006a) conducted an experimental study on the short-term
strength and deformation characteristics of salt rock samples obtained from the Jintan Salt Mine in Jiangsu. The salt rock sample from Jiangsu Jintan Salt Mine has a strong lateral deformation ability and a high Poisson’s ratio. However, its elastic modulus is relatively small, and its uniaxial compressive strength is relatively low. Liu et al. (2006b) found that during the experiment, the salt rock samples exhibited different characteristics as the confining pressure increased. When the confining pressure was less than 5 MPa, the characteristic of the sample was mainly strain softening. When the confining pressure was greater than 5 MPa, the characteristics changed from strain softening to hardening. Furthermore, Li et al. (2014), Liu et al. (2017), and Fan et al. (2019) studied the stability and permeability of salt cavern and the discontinuous fatigue of rock salt.

Casing damage is caused by numerous factors, including engineering, geological, and corrosion factors. With regard to geological factors, the main reason is the natural characteristics of the formation to be drilled. The physical properties of the various formations are extremely different owing to their composition, elastic modulus, and Poisson’s ratio. For example, the salt–gypsum layer has many thin interlayers, whereas the salt rock layer has a strong creep property. Huang et al. (2008) conducted a study on mud shale and found that the elastic modulus and uniaxial compressive strength measured in the experiment decreased as the water content increased. Therefore, the high water content greatly reduces the elastic modulus and uniaxial compressive strength of the mud shale, which causes a nonuniform squeezing on the casing. At that time, a few studies on the mechanism of casing damage using numerical simulation were very innovative. Zhang et al. (2005) conducted a 2D numerical research on casing damage in the soft rock formation with creep property. Lao et al. (2012) calculated the salt creep and well casing damage at high-pressure and high-temperature conditions. Wang et al. (2016) created a 3D geomechanical model of salt creep behavior on wellbore casing for pre-salt reservoirs. Lin et al. (2016) studied the influence of formation dip angle and formation creep on casing damage. For on-site drilling operations, a formation that has a relatively large dip angle and particularly strong creep, such as mud shale and salt–gypsum rock, is often encountered. When a formation is drilled into a formation with such formation characteristics, the possibility of wellbore damage is extremely high. Lin et al. (2016) used numerical simulation to create the damage model of mud shale water absorption creep on the casing and the plastic flow model of the salt–gypsum layer. The conclusion proves that the main type of casing damage is lateral extrusion failure.

According to the current survey statistics, most domestic and foreign experts have focused on the consideration of the engineering, geological, and chemical factors in the field of casing damage during on-site drilling operations. However, in-depth researches and analysis of the effect of interlayer deformation and creep on casing damage in the composite salt–gypsum formations are scarce.

2. Creep behavior

With regard to creep behavior, under a constant external force, salt rock deformation increases with time until it breaks. The creep characteristics of salt rock are influenced by numerous factors, such as differential stress and temperature. Moreover, creep behavior is usually in a long-term stable stage. Figure 2 presents the relationship between creep strain and time of salt rock. From the figure, it can be seen that the creep process of salt rock is divided into three stages: transient creep, steady-state creep, and accelerated creep.
Figure 2. Relationship between creep strain and time of salt rock (1. transient creep; 2. steady-state creep; and 3. accelerated creep)

Urai and Spiers (2007) conducted an in-depth study on the creep mechanism of the salt–gypsum layer. For salt rock, the creep during tectonic movement is naturally controlled mainly by the precipitation–dissolution creep mechanism and the dislocation creep mechanism. The governing equation of the precipitation–dissolution creep mechanism is as follows:

$$\dot{\varepsilon}_{PS} = B(\Delta \sigma) = B_0 \exp \left( -\frac{Q}{RT} \right) \left( \frac{\sigma_1 - \sigma_3}{TD^m} \right)$$  \hspace{1cm} (2.1)

where $\Delta \sigma = \sigma_1 - \sigma_3$ denotes the differential stress; $D$, the grain size; $Q$, the activation energy; $T$, the temperature; $R$, the gas constant ($R = 8.314 \text{ J/(mol} \cdot \text{K)}$); $B_0$, the material parameter; and $B = B_0 \exp \left( -\frac{Q}{RT} \right) /TD^m$, the rheological parameter of rock salt. In the formula, $D$ and $m$ are two important parameters: $m$ determines the creep strain rate, whereas $D$ determines the steady-state strain rate. The governing equation of the dislocation creep mechanism is as follows:

$$\dot{\varepsilon}_{DC} = A(\Delta \sigma)^n = A_0 \exp \left( -\frac{Q}{RT} \right) (\sigma_1 - \sigma_3)^n$$  \hspace{1cm} (2.2)

where $\dot{\varepsilon}_{DC}$ denotes the steady-state creep rate; $\Delta \sigma = \sigma_1 - \sigma_3$, the differential stress; $Q$, the reactivation energy; $R$, the gas constant ($R = 8.314 \text{ J/(mol} \cdot \text{K)}$); $T$, temperature; $A_0$, the material parameter; and $A_0 \exp \left( -\frac{Q}{RT} \right)$, the rheological parameter of rock salt. In the formula, $n$ determines the steady-state creep rate $\dot{\varepsilon}_{DC}$. The dislocation creep mechanism is different from the precipitation dissolution mechanism in that the particle size does not affect the size of $\dot{\varepsilon}_{DC}$, but it does affect the size of $\dot{\varepsilon}_{PS}$. The data statistics of the laboratory experiments on salt rock creep which were conducted worldwide is presented in Figure 3, including the mechanism of precipitation dissolution creep and dislocation creep (Li and Urai, 2016).
3. Triaxial creep experiment in the laboratory

The salt rock core obtained from an oilfield in the creep experiment has a coarse particle size, and it is mainly black or gray. Due to the special physical properties of salt rock, it dissolves when mixed in liquids, such as water. Therefore, to avoid damage to the test piece by water lubrication when cutting, the dry cutting method should be adopted. The test stipulates that the salt rock sample is 100 mm in length and 50 mm in diameter. First, the salt rock core column was taken out using a coring machine and drilled using a drill bit with a diameter of 50 mm. During the coring process, care was taken not to use water or other liquids as lubricating fluids. After the column center was taken out, it was dry-cut using a cutting machine. Then, a test piece was cut out according to the size requirements, and the cutting surfaces were smoothed at both ends. Figure 4 presents a salt rock sample after treatment (Li, 2020).

![Figure 4. A salt rock sample before and after creep test (Li, 2020)](image)

After the samples were processed, indoor experiments of salt rock creep were conducted on a triaxial creep test machine of the Rock Mechanics Laboratory at Sichuan University. The test machine was called the program-controlled triaxial rheological test system for rock salt. Figure 5 presents the triaxial rheological test system (Li, 2020). The axial load of the instrument is in the range of 0–600 kN, and the confining pressure is 0–30 MPa. The accuracy of the sensor is 1%. It has the function of stabilizing axial load and confining pressure after power failure for 6 months. Moreover, the test accuracy of load and pressure is better than 0.5%, displacement is better than 0.05%, and axial
deformation is less than 0.05%.

In the experiment, the temperature, humidity, and pressure should be controlled. During the whole duration of the experiment, normal temperature was maintained. The confining pressure is controlled by oil pressure. To simulate the actual situation, the selection of the confining pressure depends on the burial depth of the specimen used, and the confining pressure of the specimen with a different burial depth is also different during the experiment. The experimental machine adopts dual-bit computer and program control. The control interface is simple and intuitive, with a highly intelligent system, simple operation, convenient setting, and strong data processing ability in the later period. All data are automatically collected by the computer, and the curves can be generated on the computer screen in real time, which is convenient for intuitive operation and analysis during the experiment.

![Program-controlled triaxial rheological test system for rock salt in Sichuan University (Li, 2020)](image)

The loading scheme of the sample is as follows: the confining pressure loading rate of the sample is 2 MPa/min, and the axial pressure is loaded on the target value at a rate of 5 MPa/min. When conducting a triaxial creep test, it is important to apply the confining pressure first, followed by the axial pressure. After applying the axial pressure, the load should be kept unchanged, the curve data transmitted by the triaxial creep test machine in real time should be observed, and the experiment should be continued after judging that the salt rock sample has entered the stage of steady-state creep. The experiment can last several months. In our research, three rock salt samples were utilized in the experiment. The samples were obtained from the same underground core in the rock salt layer. The experiment on Sample 1 was conducted with a confining pressure of 5 MPa and an axial pressure of 20 MPa. It lasted for about 1 day. The experiment on Sample 2 was conducted with a confining pressure of 5 MPa and an axial pressure of 25 MPa. The experiment lasted for about 1 day. The experiment on Sample 3 was conducted with a confining pressure of 5 MPa and an axial pressure of 30 MPa. The experiment lasted for about 2 days. The final experimental results are presented in Table 1, and the curves are presented in Figure 6a, 6b, and 6c. The dotted line indicates the axial stress, and the curve indicates the axial strain.
Figure 6a. Creep curve of salt rock sample 1 (axial stress 20 MPa, dotted line)

Figure 6b. Creep curve of the salt rock sample 2 (axial stress 25 MPa, dotted line)
Figure 6c. Creep curve of the salt rock sample 3 (axial stress 30 MPa, dotted line)

Table 1. Test parameters and strain rate of salt rock specimens 1–3

| Diameter/mm | Length/mm | Confining pressure/MPa | Strain rate/s⁻¹ | Strain rate/s⁻¹ | Strain rate/s⁻¹ |
|-------------|-----------|------------------------|-----------------|-----------------|----------------|
| 49.89       | 100       | 5                      | 1.969e⁻⁸        | 3.563e⁻⁸        | 5.471e⁻⁸       |

From the creep curve obtained in this experiment, it can be seen that under the triaxial test conditions, the creep stages of salt rock are mainly the initial creep stage and steady-state creep stage. Given that this experiment did not take a long time to complete, the salt rock sample did not reach the third stage, which is the accelerated creep stage. The parameter \( n \) in the formula is one of the important rheological parameters. The magnitude of the power \( n \) affects the strain rate of the salt rock. In the subsequent numerical simulation, it is important to define the value of the rheological parameter \( n \). Combined with the fitting formula of the curve when the differential stresses are 15, 20, and 25 MPa, it is found through the calculation that when the partial stress linearly increases, \( \dot{\varepsilon}_{DC} \) also roughly exhibits a trend of linear growth. Figure 7 presents the fitting diagram. Therefore, in the subsequent numerical simulation, we will take 2 as the value of power \( n \).
Figure 7. Fitting relationship between deviator stress and $\dot{\epsilon}_{DC}$

Validation of the experiment is important in numerical simulation to maintain the accuracy of the numerical model, and it is the precondition for the 3D numerical research in our study. In the previous study, a numerical simulation test on rock salt creep was conducted according to the triaxial creep experiment in the laboratory. The method and model of the validation have been introduced in detail (Li and Urai, 2016). The axisymmetric model is adopted to model the cylindrical rock salt sample, and the axial and confining pressures are applied (Figure 8). The creep constitutive relation obtained from the experiment is provided as the material property in the numerical model. The experiment can be validated in the numerical model, and both results can be compared (Figure 9 and Table 2). The numerical result is in agreement with the experimental result. The small error between the results is caused by two influencing factors. One is that the friction on the top and bottom of the sample is neglected in the numerical simulation. The other factor is that transient creep is not included in the numerical model, because in the long-term casing damage process, the steady-state creep of rock salt plays a dominant role.
Figure 8. The axisymmetric model of the sample with axial and confining pressures

Figure 9. The displacement of the sample model after creep

Table 2. Experimental and numerical results of the triaxial creep experiment simulation

|                  | Confining pressure 5 MPa | Confining pressure 5 MPa | Confining pressure 5 MPa |
|------------------|--------------------------|--------------------------|--------------------------|
| Axial strain     | Axial pressure 20 MPa    | Axial pressure 25 MPa    | Axial pressure 30 MPa    |
| Axial strain     | 0.01                     | 0.012                    | 0.018                    |
| (experimental    |                          |                          |                          |
| result)          |                          |                          |                          |
| Axial strain     | 0.098                    | 0.0117                   | 0.01696                  |
| (numerical       |                          |                          |                          |
| result)          |                          |                          |                          |

4. Three-dimensional numerical research on casing deformation

4.1 Formation geometry and material characteristics
The finite element model established in this paper is the formation–casing–cement ring model. The formation depth is set to 1500 m and the model height to 1500 m. The specific size of the model is 300 × 300 × 1500 m, and the scale of the geometric model established accordingly is 300 × 300 × 1500 m.
Because the stratum model needs to have three parts, salt layer, mud layer, and gypsum layer, it needs to be cut on the overall 3D model (Table 3).

| Table 3. Specific parameters of the model materials |
|-----------------|-----------------|-----------------|
| Material      | Elastic modulus/GPa | Poisson’s ratio |
| Gypsum        | 40               | 0.15            |
| Rock salt     | 10               | 0.25            |
| Mudstone      | 20               | 0.24            |
| Casing        | 210              | 0.28            |
| Cement        | 2.1              | 0.25            |

Figure 10 presents the multiple-layered model. The model is divided into three parts: ① the gypsum layer, ② the salt rock layer, and ③ the mudstone layer. The bonding degree of the interface is important, because a strong or a weak bonding has an evident influence on the interface property. Interface deformation or damage is dependent on the bonding degree of the interface. In our model, the interface between different layers is assumed to be well bonded. Moreover, the interface has no thickness in the model, and the lithology exhibits a sudden change at the interface. The creep parameter of the salt rock layer is set to $A = 9 \times 10^{-11}$ MPa$^2$s$^{-1}$, $n = 2$. The initial model established is a control model, and all strata are elastic strata. The elastic modulus of layer ① is 40 GPa, and Poisson’s ratio is 0.15; the elastic modulus of layer ② is 10 GPa, and Poisson’s ratio is 0.25; and the elastic modulus of layer ③ is 20 GPa, and Poisson’s ratio is 0.24. The central part of the model is composed of the casing and cement ring, and the time duration is 10$^4$s.

**Figure 10.** The multiple-layered model

4.2 Load conditions under construction
The model disregards the effect of formation gravity to facilitate calculation. On the basis of the actual situation of the composite salt–gypsum layer, the stratum is generally several kilometers underground. In addition, due to the tectonics property, the overburden pressure of the stratum is assumed to be relatively smaller than its lateral pressure. Combined with the principle of control variables, the
overburden pressure of the model is expressed as $F_1 = 4 \times 10^7 \text{ Pa}$, whereas the lateral pressure is expressed as $F_2 = 4.5 \times 10^7 \text{ Pa}$. Due to the buffer resistance of the cement slurry inside the casing, the application of internal pressure on the casing is necessary. The specific setting is $F_3 = 3 \times 10^7 \text{ Pa}$. Finally, the displacement of the bottom of the model needs to be constrained, and the ground of the third layer is set to be immovable, that is, the displacement in the Y direction of the model is constrained to 0. A fixed part of the 3D model needs to be applied. Figure 11 presents the specific load and boundary adjustment definition.

![Figure 11](image)

**Figure 11.** Definition of load and boundary adjustment conditions

### 4.3 Result analysis

The stress contours are presented in Figures 12 and 13. In the more complete part of the stratum, the casing and cement ring are evenly stressed, and no strong and concentrated stress is applied. The stress is large only on the casing surface, but it will not cause great damage to the casing.

Considering the situation in the composite salt–gypsum formation, the stress at the interface on the casing suddenly changes due to the different properties of the upper and lower formations. Because of the sudden stress change on the casing at the interface, the upper and lower stress levels of the interface are different, causing the casing to be subjected to shear stress, which may lead to dislocation and shear failure. With the increase in production process time, the upper and lower parts of the casing at the interface will have different stress distributions and stress concentrations. In addition, stress mutation will occur near the interface, which will eventually lead to damage and scrapping of the
casing. Therefore, the interface of the formation should be the focus of protection and improvement.

![Stress contour of gypsum salt mudstone composite stratum model](image1)

**Figure 12.** Stress contour of gypsum salt mudstone composite stratum model

![Stress concentration at the interface](image2)

**Figure 13.** Stress concentration at the interface

We zoom in on the interface position of the composite salt–gypsum layer and observe the stress distribution of the casing at the interface, as presented in Figure 14. From the figure, it can be seen that the von-Mises stress in the mudstone layer and the salt rock layer significantly changes. After considering the creep, the von-Mises stress in the salt layer casing increases to $2.675 \times 10^8$Pa, and the mudstone layer casing stress is $1.339 \times 10^8$Pa. The casing produced a significant stress gap, which results in shear failure of the casing.
5. Three-dimensional finite element simulation of multiple sets of composite salt–gypsum layers

In the previous section, a 3D finite element model of the gypsum–salt–mudstone composite formation was created, which confirmed the existence of stress concentration at the interface of the composite salt–gypsum layer interface. As mentioned previously, the composite salt–gypsum layer is not only a single gypsum–salt–mudstone composite formation. Sometimes, multiple sets of composite salt–gypsum layers are stacked one after another. In this type of formation, the salt rock layer exists not only in one of the layers of the composite salt–gypsum formation but also in multiple sets of composite layers. Moreover, the geological data obtained by geological surveys indicate that the properties of different salt rock layers in the composite salt–gypsum layer are also different, as well as their elastic moduli, Poisson’s ratios, and creep characteristics.

Therefore, in this section, multiple sets of 3D finite element models of composite salt–gypsum layers are established, two salt rock layers are set up, and the elastic moduli, Poisson’s ratios, and creep characteristics of the two salt rock layers are set to be different. It can be observed whether stress concentration exists at the place, and we can also compare the impact of different salt rock layers on the casing damage.

5.1 Formation geometry and material characteristics

The finite element model established in this section is a set of 3D finite element models of composite salt–gypsum layers. The formation depth is set to 1500 m; thus, the model height is also set to 1500 m. The specific size of the model is 300 × 300 × 1500 m, and the scale of the geometric model established accordingly is 300 × 300 × 1500 m. Because the stratum model needs to have four parts, the gypsum layer, salt layer, mud layer, and salt layer, it can be cut on the overall 3D model. Table 4 presents the specific material parameters set.

| Material   | Elastic modulus/GPa | Poisson’s ratio |
|------------|----------------------|-----------------|
| Gypsum     | 40                   | 0.15            |
| Rock salt 1| 10                   | 0.25            |
| Mudstone   | 20                   | 0.24            |
The assembled model is presented in Figure 15, which is divided into four parts: ① the gypsum layer, ② the salt rock layer 1, ③ the mudstone layer, and ④ the salt rock layer 2. The center of the model is composed of the casing and cement ring. The creep parameter of salt rock layer 1 is set to $A = 1.25 \times 10^{-13} \text{MPa}^{-1}\text{s}^{-1}$, $n = 1$; the creep parameter of salt rock layer 2 is set to $A = 9 \times 10^{-11} \text{MPa}^{-2}\text{s}^{-1}$, $n = 2$.

|   |Rock salt 2| 12 | 0.23 |
|---|-----------|----|------|
|   |Casing     | 210| 0.28 |
|   |Cement     | 2.1| 0.25 |

**Figure 15.** Multiple sets of the composite layered model

### 5.2 Load conditions under construction

This model can be consistent with the load conditions of the previous model. The overlying pressure of the model is expressed as $F_1 = 4 \times 10^7 \text{Pa}$ and the lateral pressure of the model as $F_2 = 4.5 \times 10^7 \text{Pa}$. The internal pressure of the casing is expressed as $F_3 = 3\times10^7 \text{Pa}$. Finally, the displacement of the bottom of the model needs to be constrained, and the cut part of the 3D model is also fixed. Figure 16 presents the specific load and boundary adjustment definitions.
5.3 Result analysis
Figures 17, 18, 19, and 20 present the calculated stress contours. From the figures, it can be seen that the stress at the interface boundary of the composite salt–gypsum layer also induces obvious mutations, further confirming the existence of stress concentration. At the same time, it can be seen that for salt rock layer 1 and salt rock layer 2, under the same conditions and time control, the formation deformation and stress concentration at the interface increase as the creep property increases. Therefore, due to the situation of multiple sets of composite salt–gypsum formations during on-site drilling operations and production process, it is important to conduct a careful geological survey at the early stage to obtain detailed geological data. This will help in determining the formation characteristics of different salt rock formations. Moreover, special casing reinforcement for different salt rock formations needs to be carried out to reduce the damage caused by the salt rock formation creep and to further extend the service life of the casing and save the economic cost of on-site operations.
Figure 17. Stress contour of multiple complex salt–gypsum layer models

Figure 18. Stress distribution at the interface
6. Three-dimensional finite element simulation of the composite salt–gypsum layer with dip angle

In part, numerical simulations of the gypsum–salt rock–mudstone composite stratum model and of multiple sets of composite salt–gypsum layer models have been conducted separately. From the simulation results, it can be realized that the stress change at the interface position of the composite salt–gypsum layer is evident. The difference in the internal stress between the upper casing and lower casing at the interface also causes shear failure. In the actual formation, there is a certain dip angle in the different layers of the composite salt–gypsum formation. Therefore, based on the previous model, we add the role of the dip angle to observe the stress distribution at the casing interface position under the dip angle. Moreover, we determine whether there is any shear failure of the casing. The 3D finite element model with added inclination is presented in Figure 21.
Figure 21. Definition of loads and boundary adjustment conditions

Figures 22 and 23 present the calculated stress distribution on the casing. From the calculation results, it can be realized that due to the effect of the formation dip angle, a sudden stress change occurs at the interface of the composite salt–gypsum layer. The stress on the gypsum layer is $1.329 \times 10^8\text{Pa}$, and at the interface with dip angle, the stress reaches $2.65 \times 10^8\text{Pa}$; moreover, the casing stress suddenly changes at the interface of the composite salt–gypsum layer. From this, it can be realized that a sudden stress change occurs at the interface position, which causes shear failure of the casing. At the same time, by comparing the addition of the formation dip angle with the absence of the formation dip angle, it can be realized that after the formation dip angle increases, the stress difference at the interface of the casing is greater. Therefore, the addition of the formation dip angle increases the shear failure of the casing.
Figure 22. Stress contour on the casing of the composite salt–gypsum layer model with dip angle

Figure 23. Diagram of the stress distribution of the casing

7. Conclusion
In this study, triaxial experiments on salt–gypsum composite rock samples are conducted, and the power-law creep constitutive model is established. Moreover, the rheological parameter of rock salt is obtained. The creep behavior of the sample follows power-law creep with the power order \( n = 2 \). A numerical model of the stratum–casing–cement ring is established. It is confirmed that stress mutation occurs at the interface of the composite salt–gypsum layer and that stress concentration exists, which causes the shear failure of the casing. The creep property of rock salt formation intensifies the casing damage. Therefore, due to the creep characteristics of the composite salt–gypsum layer, further reinforcement and optimization design of the casing are needed. To reduce shear and creep damage to the composite salt–gypsum layer on the casing, it is important to strengthen the casing or reasonably use a cement ring to buffer.
Acknowledgments
This research is funded by the National Natural Science Foundation of China (No. 51704307) and is supported by the Science Foundation of China University of Petroleum-Beijing (No. ZLZX2020019), supported by the National Science and Technology Major Special Project (2016ZX05046-04) and supported by China Petroleum Strategic Cooperation Technology Project (ZLZX2020-02).

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