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STUDY OF FACTORS OF INFLUENCE ON CREEP LAW OF EXTENDED REACH WELL IN SALT ROCK LAYER

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АНАЛІЗ ВПЛИВУ РЕОЛОГІЧНИХ ФАКТОРІВ У СОЛЯНИХ ПЛАСТАХ НА ЗАКОНОМІРНОСТІ ЗНАЧНОГО ЗМІЩЕННЯ СВЕРДЛОВИН

Purpose. The authors aim to develop a new 3D analytical creep model for directional wells, and to identify the rules of wellbore shrinkage under the action of stress in thick salt-gypsum layer in Middle East fields, which will reduce the risk of drilling sticking accidents during the process of drilling of an extended reach well.

Methodology. Based on the viscoelastic theory, the Kelvin-Voigt creep model was applied to deduce a new three-dimensional analytical creep model for extended reach well, by combining the inclined shaft lining stress formula in the rectangular coordinate system and cylindrical coordinate system. By means of this model, the creep law of salt rock under different drilling fluid density, creep time, azimuth, and well drift angle has been quantitatively analyzed.

Findings. The new three-dimensional analytical creep model for an extended reach well has been derived. The relationship between the borehole radial displacement of salt rock layer and different influencing factors, such as the inclination angle, the azimuth angle, drilling fluid density and the borehole spud time, has been analyzed.

Originality. The three-dimensional analytical creep model for extended reach well describing adequately the relationship between salt rock layer creep law and influencing factors, which is different from the current analysis models that are usually studied by 2D plane analysis model or finite element method for numerical simulation, has been developed.

Practical value. The three-dimensional analytical creep model has been created for determining the rules of wellbore shrinkage under different influencing factors. The results of the analysis of the salt rock layer creep can provide significant guidance for extended reach well to be drilled through salt rock layer successfully.

Keywords: *creep in salt rock layer, creep time, drilling fluid density, inclination angle, azimuth angle*

Introduction. With the development of economy, many subsalt reservoirs are developed, whereas salt rock creep will cause serious issue for the drilling safety [1–3]. Many scholars have done various research work on the vertical wellbore creep problem in the salt rock layer [4–6]. However, with the exploration and development efforts constantly increase, vertical wells production capacity in the rock salt layer is limited and cannot satisfy the need of production. Especially in recent years our country gets oil and gas exploration rights in the Middle East, huge amounts of extended reach well in the salt rock layer need to be drilled, so creep problems for extended reach well in the salt rock layer need to be solved as soon as possible.

Some salt rock drilling history of horizontal drilling wells shows that the inclined shaft built in the salt rock layer always causes problems like borehole shrinkage and casing deformation and so on.

In order to solve the problems that salt rock section is easy to have creep borehole diameter contraction, Zeng Dezhi et al. (2007) applied the method of numerical simulation and built space mechanics model that is used to describe the inclined shaft borehole creep in the salt rock layer [7].

Lou Yishan et al. (2008) built the three-dimensional directional well creep model on the basis of spatial coordinate transformation; the modal made the stress change in inclination angle and azimuth display in the well-axis coordinate system [8].

Lin Yuanhua et al. (2012) applied the ADINA finite element software to study sandstone and salt rock formations in the area that inclined shaft made in salt rock layer, cement sheath and sleeve coupling three-dimensional mechanical model; the research showed the influence rules of the inclination and azimuth to borehole diameter narrowing [9].

Their research is based on the finite element software to analyze the creep law of salt rock layer, and it is not good enough to display the relationship of creep law of salt rock layer and influencing factors. Therefore, for this study, it deduces the three-dimensional analytical model of directional wells in the salt rock layer, which can be used to provide the guidance for the drilling of extended reach wells in the Middle East.

Theoretical Model. Supposing formation original stress and direction is known, rock stress distribution around the borehole is established by using the following method. Take overburden pressure σ_3 along the vertical direction, another two geostresses σ_1 and σ_2 along the vertical and along the horizontal direction, which is shown in Fig. 1. For convenience, while using Cartesian coordinate system *xyz* and cylindrical coordinates system $r\theta z$ to represent the inclined shaft borehole, P_0 is pore pressure, supposing inclined shaft borehole a α, relative σ_1 the azimuth angle a φ. By rotating the coordinate system geostresses $\sigma_1, \sigma_2, \sigma_3$ and $\sigma_x, \sigma_y, \sigma_z$ conversion relationship can be set up. Firstly, around the three axes turn counterclockwise φ to be coordinate system as $x_1y_1z_1$, and then around y_1 axis turn counterclockwise α to be coordinate system as *xyz.*

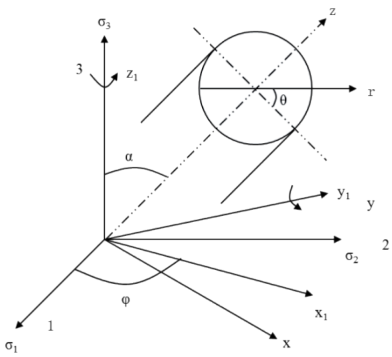

Fig.1. Borehole coordinate transformation diagram

The conversion relationship between the new coordinate system *xyz* and coordinate system 123 can be shown by the transformation matrix [10]

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\varphi\cos\alpha & \sin\varphi\cos\alpha & -\sin\alpha \\ -\sin\varphi & \cos\varphi & 0 \\ \cos\varphi\sin\alpha & \sin\varphi\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}. \quad (1)$$

Considering the two coordinate systems, stress components conversion relationship is

$$\begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} = \begin{bmatrix} \cos\varphi\cos\alpha & \sin\varphi\cos\alpha & -\sin\alpha \\ -\sin\varphi & \cos\varphi & 0 \\ \cos\varphi\sin\alpha & \sin\varphi\sin\alpha & \cos\alpha \end{bmatrix} \times \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} \times$$
$$\times \begin{bmatrix} \cos\varphi\cos\alpha & -\sin\varphi & \cos\varphi\sin\alpha \\ \sin\varphi\cos\alpha & \cos\varphi & \sin\varphi\sin\alpha \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix}. \quad (2)$$

Supposing rock is linear elastic and isotropic, at the same time the rock surrounding a borehole is in the plane strain state, then the displacement of the radial stress σ_r and tangential stress σ_θ around the borehole is as follows

$$\sigma_r = \frac{1}{2}\left(\sigma_x + \sigma_y\right)\left(1 - \frac{a^2}{r^2}\right) + \frac{1}{2}\left(\sigma_x - \sigma_y\right)\left(1 + 3\frac{a^4}{r^4} - 4\frac{a^2}{r^2}\right)\cos 2\theta +$$
$$+\tau_{xy}\left(1 + 3\frac{a^4}{r^4} - 4\frac{a^2}{r^2}\right)\sin 2\theta + \frac{a^2}{r^2}P_a;$$
$$\sigma_\theta = \frac{1}{2}\left(\sigma_x + \sigma_y\right)\left(1 + \frac{a^2}{r^2}\right) - \frac{1}{2}\left(\sigma_x - \sigma_y\right)\left(1 + 3\frac{a^4}{r^4}\right)\cos 2\theta -$$
$$-\tau_{xy}\left(1 + 3\frac{a^4}{r^4}\right)\sin 2\theta - \frac{a^2}{r^2}P_a. \quad (3)$$

In the formula:
P_a is the drilling fluid pressure in the wellbore;
r is the radial distance to the center of the borehole;
a is the wellbore radius.

The Creep Model applies the Kelvin - Voigt model

$$2e_{ij} = \left(\frac{1}{G_H} - \frac{G_H + G_K}{G_H G_K}\right) s_{ij}^c e^{-\frac{G_K}{\eta_K}t} + \frac{G_H + G_K}{G_H G_K} s_{ij}^c. \quad (4)$$

In the formula:
e_{ij} is deviatoric stress tensor;
G_H is the shear modulus in H's spring, Mpa;
G_K is the shear modulus in K's spring, Mpa;
s_{ij}^c is the constant of the stress deviator tensor, Mpa.

To simplify the derivation, the formula in (4) is simplified taking G_0, G_∞, T_{ret} into the formula, the simplified equation can be expressed the following way

$$2e_{ij} = \left(\frac{1}{G_0} - \frac{1}{G_\infty}\right) S_{ij}^c e^{-t/T_{ret}} + \frac{1}{G_\infty} S_{ij}. \quad (5)$$

In the formula:
G_0 is the initial shear modulus, Mpa;
G_∞ is the long-term shear modulus, Mpa;
T_{ret} is the delay time, s;
t is the creep time, s.

By using polar coordinates we expand the formula as follows

$$2\left(\varepsilon_r - \varepsilon_m\right) = \left(\frac{1}{G_0} - \frac{1}{G_\infty}\right)\left(\sigma_r - \sigma_m\right) e^{-t/T_{ret}} + \frac{1}{G_\infty}\left(\sigma_r - \sigma_m\right). \quad (6)$$

In the formula:
σ_m is average stress, Mpa;
ε_m is average strain, %.

Borehole deformation belongs to generalized plane strain issue; thus

$$\sigma_m = \frac{1+v}{3}\left[-\frac{1}{2}\left(\sigma_x - \sigma_y\right)\frac{4a^2}{r^2}\cos 2\theta + \tau_{xy}\frac{4a^2}{r^2}\sin 2\theta + \sigma_x + \sigma_y\right]. \quad (7)$$

On the basis of the relationship between the average strain and average stress, the following formula can be obtained

$$\varepsilon_m = \frac{1+\mu}{3E}(1-2\mu)\left[\left(\sigma_x+\sigma_y\right)-\frac{1}{2}\left(\sigma_x-\sigma_y\right)\frac{4a^2}{r^2}\cos 2\theta-\tau_{xy}\frac{4a^2}{r^2}\sin 2\theta\right]; \quad (8)$$

$$\varepsilon_r = \frac{\partial u}{\partial r}\ . \quad (9)$$

For (1–9) simultaneous equations can be obtained as follows

$$u=\frac{1}{2}\left\{\begin{aligned}&-\frac{a^2}{r^2}P_a+\frac{1}{2}\left(\sigma_x+\sigma_y\right)\left(r+\frac{a^2}{r}\right)+\frac{1}{2}\left(\sigma_x-\sigma_y\right)\left(r-\frac{a^4}{r^3}+\frac{4a^2}{r}\right)\cos 2\theta\\&+\tau_{xy}\left(r-\frac{a^4}{r^3}+\frac{4a^2}{r}\right)\sin 2\theta-\frac{1+\mu}{3}\left[\left(\sigma_x+\sigma_y\right)r+\frac{1}{2}\left(\sigma_x-\sigma_y\right)\frac{4a^2}{r}\cos 2\theta+\tau_{xy}\frac{4a^2}{r}\sin 2\theta\right]\end{aligned}\right\} \quad (10)$$
$$\times\left[\left(\frac{1}{G_0}-\frac{1}{G_\infty}\right)e^{-t/T_{ret}}+\frac{1}{G_\infty}\right]+\frac{1+\mu}{3E}(1-2\mu)$$
$$\times\left[\left(\sigma_x+\sigma_y\right)r+\frac{1}{2}\left(\sigma_x-\sigma_y\right)\frac{4a^2}{r}\cos 2\theta+\tau_{xy}\frac{4a^2}{r}\sin 2\theta\right]+f(\theta)$$

In the formula, $f(\theta)$ is a rigid displacement item, provided the origin of coordinate is chosen at the center of the borehole, $f(\theta)=0$.

While u is the absolute displacement, the relative displacement is as follows

$$u' = u - u_0\ .$$

In the formula, u_0 is the initial displacement of the borehole.

Supposing $r = a$, the relative displacement of the borehole can be obtained as follows

$$u'_a=\frac{a}{2}\left\{-P_a+\frac{2-\mu}{3}\left[2\left(\sigma_x-\sigma_y\right)\cos 2\theta+4\tau_{xy}\sin 2\theta+\sigma_x+\sigma_y\right]\right\}\left[\left(\frac{1}{G_0}-\frac{1}{G_\infty}\right)e^{-t/T_{ret}}+\frac{1}{G_\infty}\right]-$$
$$-\frac{a}{2G_0}\left[\frac{1}{2}\left(\sigma_x-\sigma_y\right)\cos 2\theta+\tau_{xy}\sin 2\theta+\frac{1-2\mu}{6}\left(\sigma_x+\sigma_y\right)\right]+ \quad (11)$$
$$+\frac{2a}{3E}(1+\mu)(1-2\mu)\left[\left(\sigma_x-\sigma_y\right)\cos 2\theta+2\tau_{xy}\sin 2\theta\right].$$

The above formula presupposes that when the borehole in salt rock layer occurs to creep, the relationship is to be between borehole radial displacement and inclination angle, azimuth angle, drilling fluid density, borehole drilling time. Considering the fact that this relationship is to be taken advantage of, it is worth discussing the impact of these variables on the creep law.

The Analysis of the Creep Law According to stress data of the oilfield Low Fars layer, the salt rock layer is influenced by abnormally high pressure, so rock stress level rises. According to the geostress portfolio the following scheme occurs: the maximum horizontal stress > vertical geostress > minimal horizontal stress. Under this specific geostress condition, the analysis of the impact of drilling fluid density, inclination angle, azimuth angle, and creep time on the salt rock borehole diameter contraction was conducted; the basic parameters are shown in Table.

The Creep Law of Salt Rock under Different Fluid Density. In this paper, the numerical value of the borehole shrinkage is calculated when the drilling fluid density under the condition of 1.8g/cm^3, 2.0g/cm^3, 2.2g/cm^3 and 2.3g/cm^3, and the creep time is 12h, 72h and 360h; a part of the borehole deformation diagram is displayed in Fig. 2, 3 .

Based on the chart above, the wellbore is no longer circular but elliptical in a non-uniform stress field. As the drilling fluid density increases, the ovality of borehole deformation increases, drilling fluid density has a big impact on borehole deformation. Borehole deformation is the biggest at the direction of the maximum horizontal stress and is the smallest at the direction of the minimum horizontal stress. As time passes by, the degree of borehole diameter contraction constantly expands, and sticking risk for borehole diameter contraction increases.

Table

Basic Parameter

Depth /m	E /Mpa	μ	Vertical Stress /Mpa	Maximum Horizontal Stress /Mpa
2500	7000	0.4	56.25	61.25
Minimal horizontal Stress / Mpa	Initial caliper / mm	G_H / Mpa	G_K / Mpa	η_K / mPa.s
52.5	311.15	124.61	61.25	3.218×10^7

Fig. 2 shows the complete diameter shrinkage. Fig. 3 shows diameter enlargement around the major axis, and diameter shrinkage around the minor axis, which means that with the mud density reaching a certain condition the forms of borehole deformation change and it has a significant impact on drilling.

Fig. 4 shows the change curve of the shaft collar section versus time under different drilling fluid density when both maximum horizontal principal stress and minimum horizontal stress occur.

From Fig. 4, 5 given above it follows that the initial deformation is large along the direction of the maximum (minimum) principal horizontal stress, under the effect of external load. As the time passes by, gradually deformation rate decreases, and eventually comes nearly to zero, which supposes that borehole shrinkage reaches a certain level, then it will stop it. This is usually true in the actual drilling work.

Regarding the borehole shrinkage along the direction of the large principal horizontal stress, the drilling fluid is more dense whereas the borehole shrinkage is greater; along the direction of the minimum principal stress, the sensitive range of the drilling fluid exists. When the drilling fluid density is less than a certain range, shaft collar shows borehole shrinkage, when drilling fluid density is greater than a certain range, shaft collar performs borehole diameter expansion.

Creep Law of Salt Rock within Different Time Spans. In order to analyze the creep law of salt rock versus time, the figure of shaft collar contraction rate change with time is made, Fig. 6. According to the actual drilling experience, for the drilling safety borehole shrinkage rate at the rate of 0.001/h is allowed.

From the figure above, at the initial moment shaft collar shrinkage rate is great. As time increases, shaft collar shrinkage rate decreases rapidly, when the creep time is more than 70h, the rate is nearly 0; under the different drilling fluid density, the time to reach the borehole shrinkage rate of safe drilling is different: the more dense the drilling fluid is, the shorter is the time.

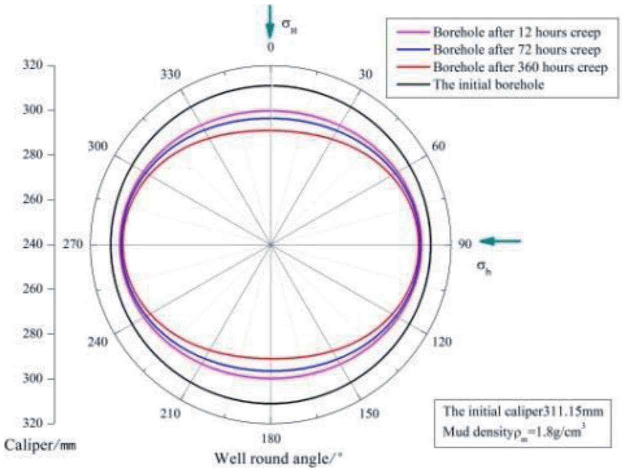

Fig. 2. Borehole deformation diagram with the drilling fluid density of 1.8g/cm^3

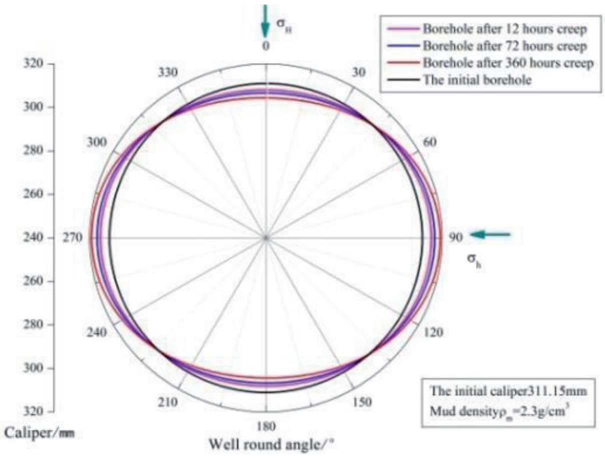

Fig. 3. Borehole deformation diagram with the drilling fluid density of 2.3g/cm^3

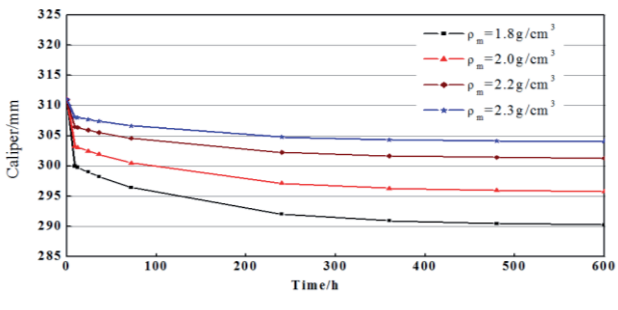

Fig. 4. Ratio curve between the drilling fluid density and hole shrinkage in the direction of σ_H

The Salt Rock Creep Law under Different Inclination Angle and Azimuth Angle. For this part, it has been analyzed that when the mud density is 2.28 g/cm^3, the creep time is 48h, under different azimuths, the borehole deformation in the salt rock layer changes with angle inclination, which is presented in Fig.7, 8.

Regarding the borehole deformation, Fig. 7, 8 show the following: when the azimuth angle along the 0°, 90° increases, the angle between caliper minor axis and the maximum horizontal stress will be presented in a counterclockwise direction showing the change of 0°, 90°. As the inclination angle increases, shaft collar along the minor becomes smaller; shaft collar along the prolate axis becomes bigger.

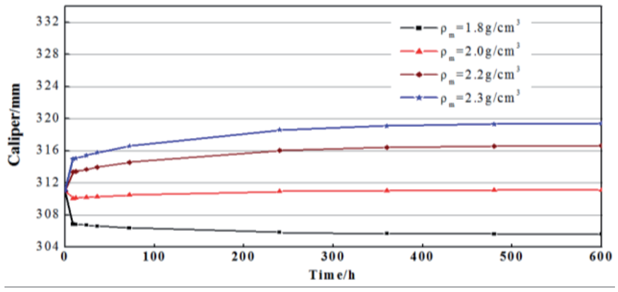

Fig. 5. Ratio curve between the drilling fluid density and hole shrinkage in the direction of σ_h

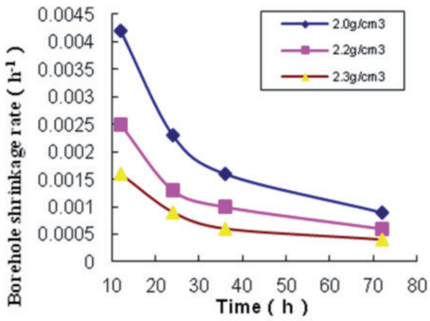

Fig.6. Ratio Curve between Borehole Shrinkage Rate and Time

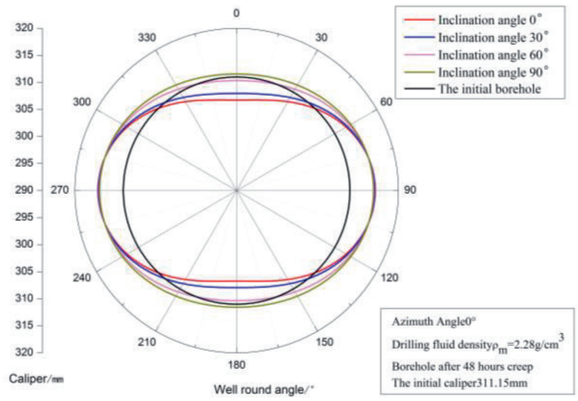

Fig. 7. Borehole deformation diagram with 0° azimuth angle

On the basis of Fig. 9, under any azimuth angle, the long axis of borehole decreases with the increase of the inclination angle. The minor changes of the inclination angle will lead to a greater creep especially within the range of 30–70°, and the risk of drilling directional wells in salt rock significantly increases. Under the same inclination angle, with the increase of the azimuth angle, the shrinkage of borehole gradually increases, and it means that the larger the deviation from the direction of maximum horizontal stress is, the more dangerous drilling will be.

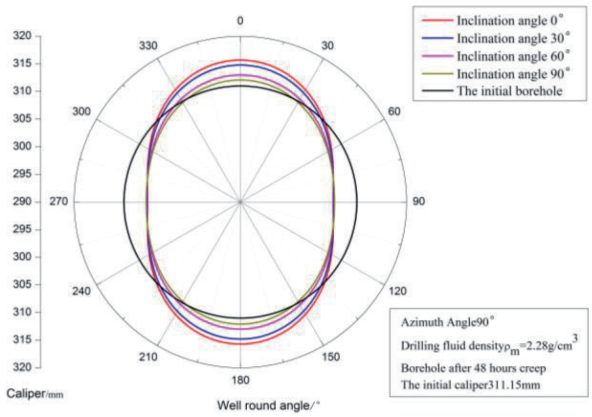

Fig. 8. Borehole deformation diagram with 90° azimuth angle

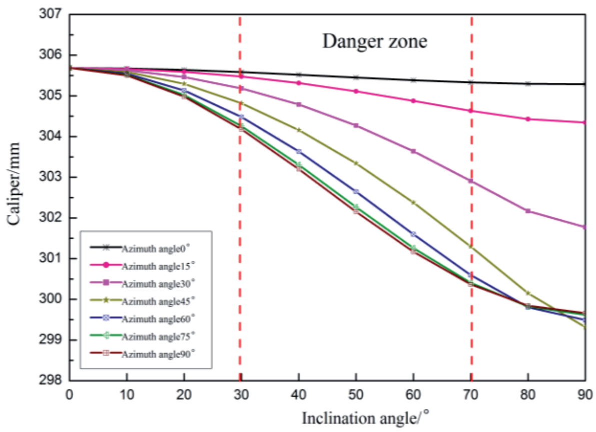

Fig. 9. Relationship between Length of Major Axis and Angle of Azimuth and Inclination Angle

Conclusion.

1. According to the viscoelastic theory, with the application of the Kelvin-Voigt creep model, and deviated wellbore stress distribution under the cylindrical coordinates, a new analytical creep model of rock salt is derived; it can demonstrate the relationship between the well borehole radial displacement and the inclination angle, the azimuth angle, drilling fluid density, and the borehole spud time.

2. Drilling fluid density has a great impact on the borehole deformation; as drilling fluid density increases, the ovality of borehole deformation increases. Moreover, the deformation of borehole in the direction of the long axis is the largest, and the deformation of borehole in the direction of short axis is the smallest. In the direction of the long axis, the caliper shows complete diameter shrinkage; the greater the fluid density is, the more serious diameter shrinkage occurs. In the direction of the short axis, the sensitive range of drilling fluid density is apparent: when the drilling fluid density is less than a certain range, the caliper shows diameter shrinkage; when the drilling fluid density is larger than a certain range, the caliper shows diameter enlargement.

3. With the passage of time, the problem of diameter shrinkage of the borehole is becoming more serious, the risk of diameter shrinkage and sticking increases. Regardless of the direction of the long axis or short axis, the rate of diameter shrinkage is relatively large at the initial moment and the initial deformation is relatively large; however, as the creep time increases, the rate of diameter shrinkage rapidly decreases, and with the time being sufficient, the rate of diameter shrinkage is nearly zero.

References / Список літератури

1. Holt, C.A. and Johnson, J.B. 1986. A method for drilling moving salt formations drilling and under reaming concurrently. *SPE Drilling Engineering*, no. 4, pp. 315–324.

2. Yang Henglin, Chen Mian and Jin Yan, 2006. Analysis of casing equivalent collapse resistance in creep formations. *Journal of University of Petroleum*, China, no. 4, pp. 94–96.

3. Pattillo, P.D., Last, N.C. and Asbill, W.T., 2003. Effect non-uniform loading on conventional casing collapse resistance. In: *SPE Drilling Conference*, February 19–21, Amsterdam, Netherlands, SPE 79871.

4. Zeng Yijin, Yang Chunhe and Chen Feng, 2002. Numerical analysis of creeppressing stress of casing in deep salt rock stratum. *Chinese Journal of Rock Mechanics and Engineering*, no. 4, pp. 595–598.

5. Willson, S.M., Fossum, A.F. and Fredrich, J.T., 2003. Assessment of salt loading on well casings. In: *SPE Drilling & Completion*, March, SPE 81820.

6. Barker, J.W. and Tsao, Y.H., 1992. Drilling long salt sections along the US Gulf Coast. In: *SPE Drilling & Completion*, September, SPE 24605.

7. Zeng Dezhi, Lin Yuanhua and Li Liuwei, 2007. Stability study on high angle well in salt rock. *Acta Petrolei Sinica*, no. 3, pp. 124–130.

8. Lou Yishan, Li Zhonghui and Zhang Chunyang, 2008. The impact of hole drift angle and azimuth on salt rock creep. *Chinese Journal of Rock Mechanics and Engineering*, no. 2, pp. 3570–3574.

9. Lin Yuanhua, Zeng Dezhi and Lu Yafegn, 2012. Numerical simulation on kick-off borehole undergauge and outside casing load of salt rock. *Rock and Soil Mechanics*, no. 2, pp. 585–589.

10. Yu Baoping, Xu Suguo and Zhao Yan, 2006. Experimental study and theoretic analysis on creep property of rock salt interlayer. *Journal of Taiyuan University of Technology*, no. 2, pp. 123–126.

Мета. Полягає у створенні нової тривимірної аналітичної моделі повзучості похило направленої свердловини та визначенні законів усадки бурової свердловини під дією напруги в масивних соляних пластах нафтового родовища Середній Схід, що зможе зменшувати аварійний ризик прихвату бурового долота при бурінні свердловини з великим зміщенням.

Методика. На основі теорії в'язкопружності була виведена аналітична тримірна модель повзучості свердловини з великим зміщенням забою по відношенню до устя із застосуванням моделі повзучості Кельвіна- Фойхта, для чого були поєднані формули напруги стінки нижньої похилої свердловини у прямокутній системі координат і циліндровій системі координат, виведений аналітичний вираз тривимірної повзучості свердловини у великому зсуві. За допомогою цієї аналітичної моделі проведений кількісний аналіз законів повзучості в соляних пластах за різної щільності бурового розчину, часу повзучості, різних азимутних кутах і кутах відхилення свердловини від вертикалі.

Результати. У роботі виведена нова тривимірна аналітична модель повзучості похило направленої свердловини. Виконаний аналіз законів змін радіального зсуву бурової свердловини з різним азимутним кутом, кутом відхилення свердловини, щільністю бурового розчину, часом повзучості в соляних пластах.

Наукова новизна. На відміну від наявних методів, заснованих на двомірній аналітичній моделі, або на чисельному моделюванні за допомогою кінцевих елементів, запропонована тривимірна аналітична модель повзучості похило направленої свердловини точно виражає відношення між законами повзучості та чинниками впливу в соляних пластах.

Практична значимість. Створена тривимірна аналітична модель повзучості для визначення закономірностей усадки стінки свердловини під впливом різних факторів. Результат аналізу повзучості соляних пластів грає важливу роль при бурінні похило направлених свердловин з більшим зміщенням вибою по відношенню до устя.

Ключові слова: *повзучість соляних пластів, тривимірна аналітична модель у великому зсуві, час повзучості, щільність бурового розчину, кут відхилення свердловини, азимутний кут*

Цель. Заключается в создании новой трехмерной аналитической модели ползучести наклонно направленной скважины и определении законов усадки буровой скважины под действием напряжений в массивных соляных пластах нефтяного месторождения Средний Восток, что сможет уменьшить аварийный риск прихвата бурового долота при бурении скважины с большим смещением забоя по отношению к устью.

Методика. На основе теории вязкоупругости была выведена аналитическая трехмерная модель ползучести скважины с большим смещением забоя по отношению к устью с применением модели ползучести Кельвина-Фойгта, для чего были совмещены формулы напряжений стенки наклонной скважины в прямоугольной системе координат и цилиндрической системе координат. С помощью этой аналитической модели проведен количественный анализ законов ползучести в соляных пластах при разной плотности бурового раствора, времени ползучести, разных азимутальных углах и углах отклонения скважины от вертикали.

Результаты. В работе выведена новая трехмерная аналитическая модель ползучести наклонно направленной скважины. Выполнен анализ законов изменения радиального смещения буровой скважины с разным азимутальным углом, углом отклонения скважины, плотностью бурового раствора, временем ползучести в соляных пластах.

Научная новизна. В отличие от имеющихся методов, основанных на двухмерной аналитической модели, или на численном моделировании с помощью конечных элементов, предложенная трехмерная аналитическая модель ползучести наклонно направленной скважины точно выражает отношения между законами ползучести и факторами влияния в соляных пластах.

Практическая значимость. Создана трехмерная аналитическая модель ползучести для определения закономерностей усадки стенки скважины под влиянием различных факторов. Результат анализа ползучести соляных пластов играет важную роль при бурении наклонно направленных скважин с большим смещением забоя по отношению к устью.

Ключевые слова: *ползучесть соляных пластов, время ползучести, плотность бурового раствора, угол отклонения скважины, азимутальный угол*

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