Calculation Model for Stick—Slip Deformation in Weak Horizontal Structural Surface Formation after Water Inflow

Chaoyang Hu, Fengjiao Wang,* and Chi Ai

ABSTRACT: In the process of reservoir exploration, the weak horizontal structural surface easily slips and cracks, and casing shearing often occurs during the formation process, which significantly affects the economic viability and effective development of oilfield. Additionally, repeated damage at the same casing position indicates the possibility of numerous cracks in the weak structural surface. In this study, we propose the geomechanical stick—slip theory to verify the above phenomenon. The stress calculation method for the weak horizontal structural surface in the upper part of the reservoir is devised under the influence of inter-regional pore pressure differences. Based on the process of accumulation—release—reaccumulation—rerelease in the formation and deformation processes, we construct the calculation model of shear stress release and slips on the cracked surface. While considering the influence of water inflow on the cracked surface, the pressure exerted on the formation stick—slip is analyzed. Then, the model was verified by the data of block X in the Daqing oilfield. The results demonstrate that under wet conditions, the maximum static and dynamic frictional stresses on the cracked surface decrease significantly, and this makes the cracked surface more prone to a greater slip degree. After the weak horizontal structural surface cracks and slips occur for the first time, the pressure difference between regions required for formation of the next slip decreases significantly. With the continuous formation of slips, the slip range gradually expands with an increase in inter-regional pressure variance. The research work in this study provides a theoretical basis for the prevention and control of casing damage in oil development zones.

1. INTRODUCTION

During the oil production process, the formation of a relative slip causes casing damage that significantly affects the oil production efficiency. In China, instances of casing damage caused by formation slips are common worldwide. Heavy oil reservoirs, such as Cold Lake in Canada, and Northern Alberta in Canada, injected a significant volume of high-pressure hot steam oil, resulting in cracks and slips in the upper shale beds and extensive casing damage. The reservoir pressure decreases with an increase in oil flooding, resulting in formation subsidence, fault reactivation or slips, and extensive casing damage in oilfields whose upper reservoirs contain horizontal faults or weak structural surface formations, such as Ekofisk oilfield in Norway, Wilmington oilfield in the United States, and Block 623 in Matagorda Island. In the Daqing oilfield in China, owing to the existence of a weak horizontal structural surface, under the condition of long-term water flooding, the relative slip of formations occurs and extensive casing shear damage also occurs at this weak horizontal structural surface. Li et al. first proposed the formation damage possibility caused by changes in pore pressure after water inflow on the bases of field data monitoring. Since then, numerous scholars have conducted related research work.

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the formation surface. His research not only verified the severity of the influence of the injection-production relationship on reservoir deformation but also realized the quantitative characterization of rock mass stress and deformation. Based on the test data, Schwall and Denney described the deformation characteristics of the casing after settlement occurred in the reservoir and confirmed that the phenomenon of weak structural surface sliding was caused by the changes in pressure. Appertaining to the cracked condition of the weak structural surface, the mechanism of casing shear damage caused by the overall slip of the weak structural surface under injection-production pressure was proposed. In accordance with the Mohr–Coulomb criterion and effective stress principle, Huang et al. analyzed the slip mechanism of a fault interface and obtained an estimation method for extreme pore pressure when a weak structural surface slid.

For water-flooding oilfields, water injection causes dilation and deformation of the formation rock. The formation and deformation caused by the injection included elastic pore and shear expansions. A higher pore pressure leads to tensile and shear failure. The increase in pore pressure changes the matrix stress and strain of the reservoir rock, and the difference in pore pressure on the plane will lead to uneven deformation of the formation. The difference in reservoir longitudinal deformation can produce shear stress on the vertical section, and the shear stress is concentrated in the middle of the formation. The shear stress on the weak interfaces (such as fractures/joints/beddings/faults) of the formation increases. The shear stress is concentrated in the middle of the formation and the shear stress is concentrated in the middle of the formation. The shear stress on the weak interfaces (such as fractures/joints/beddings/faults) of the formation increases along with the decreasing normal and frictional stresses; thus, formation is likely to slide along weak interfaces. Fault activity can be initiated in two ways: by reactivating existing faults and generating new fractures or faults. The tensile failure, shear failure, and pore collapse caused by water injection can be interpreted from the results of the microseismic interpretation. In-room experiments demonstrated that the pressure difference could produce a progressive slip with a maximum slip displacement of 15 mm. According to the report, the casing damage rate in water-driving fields is very high. There is 88% casing damage in the S-1 block in the Daqing oilfield, and most of the casing damage was caused by slip on the weak interfaces. During the increase of the number of casing-damaged wells, the cumulative ground rise in this block is 0.4 m. A similar encounter also occurred in the Qinghai, Tarim, and Jilin oilfields. Casing damage significantly affects oil production; therefore, it is a key technical problem that needs to be solved in water injection development. Huang et al. inferred that the high pressure and hydration of mudstone induced the sliding of beddings or interlayers and consequently caused casing failure. Han et al. concluded that the sandstone layer expanded and claystone slid, causing casing failure in the Daqing oilfield. The main failure modes of the casings include deformation and dislocation. Yin et al. inferred that the slip of a weak structural surface caused casing damage deformation in water-flooding oilfields. It is well known that formation slip is a continuous process; however, previous studies have only obtained the conditions and laws of the first formation slip. After the first formation slip, there is residual shear stress on the weak structural surface that appears as an accumulation–release–reaccumulation–rerelease process in the formation and deformation processes, and its essence is the stick–slip effect.

Stick–slip is a type of stage friction instability phenomenon. In geological tectonics, the stick–slip theory is used to study the deformation law of faults under the influence of long-term geological tectonic forces. Theoretical research on the stick–slip phenomenon mainly focused on the frictional criterion related to velocity and state, and a substantial number of laboratory studies have also revealed its periodic mechanical process. Hu considered the influence of slip weakening after surface fracture and studied the intermittent stick–slip deformation law of a horizontal plane under formation pressure. Dorostkar and Carmeliet used the coupled discrete element and computational fluid dynamics methods to study the stick–slip characteristics of a shear grain fault gouge and compared the stick–slip event characteristics of a fault gouge under wetting and nonwetting conditions. van de Ende and Niemeijer used a numerical simulation of the external force mode with a dynamic change in pressure over time to provide an explanation for the regular stress drop and intermittent sliding deformation manifested in laboratory stick–slip. Li et al. used the step function of the time-varying initial damage to qualitatively describe the stick–slip deformation of shear bands caused by the formation of microcracks at different times during the cracking process of brittle rock, and they obtained the internal reasons for the stress drop caused by shear fracture and frictional stick–slip. So and Capitanio calculated the slip according to the strain rate response and obtained the step function shape of the fault slip amount, reproducing the strict periodic dynamic stick–slip process under the condition of two faults. For the water-driven oilfield with a weak horizontal surface, under the influence of the deformation of the bottom oil layer, the weak horizontal surface slid repeatedly for a long time, and the crack surface underwent stick–slip deformation. Moreover, owing to long-term water-flooding development, the stick–slip crack surface has been flooded significantly. Therefore, the slip criterion of a weak structural surface after water inflow and the calculation of stick–slip deformation are important research areas to be worked on.

Based on the stick–slip deformation theory, the calculation of slip deformation of weak structural surfaces has not been previously reported. In this study, a stick–slip mechanical model of a weak horizontal structural surface was constructed according to the influence of the pore pressure difference between formations, and the approximate analytical solutions of the formation stress and displacement were obtained. Based on the fault stick–slip and slip weakening theories, a stick–slip deformation calculation model of the weak horizontal structural surface after water intake was constructed, and the relative slip distance of the weak structural plane was quantitatively characterized.

2. CALCULATION MODEL

2.1. Stress Calculation Model of Weak Horizontal Structural Surfaces. The average formation pressure difference between adjacent regions is the source of the force that causes uneven settlement of strata, induces damage, and results in a slip of weak structural surfaces. Generally, a reservoir is divided into several blocks, each with a corresponding development scheme. Although there may be variations in injection-production pressure between different development layers and patterns within the same block, a similar average formation pressure is generally maintained within the block. However, the average formation pressure difference between adjacent blocks can be approximately 1 MPa, and in some cases more than 2 MPa, owing to the different designs of
injection—production formation pressure, thereby increasing injection formation pressure to increase production, drilling shutdowns, or casing damage shut-ins. For instance, in the Daqing oilfield, mud shale is widely distributed in the upper part of the oil reservoir. Owing to the existence of a weak horizontal structural surface in mud shale, a large scale of this weak structural surface has cracked in numerous areas. A diagram of the relative position of the reservoir and the weak horizontal structural surface is shown in Figure 1.

It is assumed that the average pore pressure of the original formation is similar in the entire reservoir. With the oilfield development, a certain radius is gradually formed for the fluff influence between regions. According to the continuous conditions of stress, strain, and displacement, at the interface of the oil and cap layers and the zero-stress boundary condition on the surface, the undetermined coefficients $a_w, b_w, a_w$, and $b_w$ are derived. Before the weak horizontal structural surface cracks, the analytical solution can be simplified, and the formation displacement field expressed after simplification is as follows:

$$w(r, z) = a_w \exp(h_f \rho r^2)$$

$$u(r, z) = a_r \exp(h_f r^2)$$

where $a_w, b_w, a_w$, and $b_w$ represent undetermined coefficients that can be functions of $z$ but not of $r$.

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$$\begin{equation}
\begin{aligned}
&\{u(r, z) = c_{uw} \exp(S_{uw}(c_{uw} h_m + c_{w0}) r^2) \\
&w(r, z) = \alpha \Delta p
\end{aligned}
\end{equation}$$

where $h_m$ represents the thickness of the overburden (m), $c_{uw}$ denotes the lateral displacement coefficient, $S_{uw} c_{uw}, c_{w1}$, and $c_{w0}$ are the radial position coefficients of lateral displacement, and $\alpha$ denotes the longitudinal displacement coefficient, and their expressions are as follows:

$$\alpha = \frac{0.250 \sigma_0}{E} \exp(\frac{-3(1-\mu)}{2(1+\mu)\eta_0})$$

$$c_{uw} = (1+\mu)(1-2\mu) \frac{0.250(1+\mu)(1-2\mu) \alpha h_\theta \Delta p}{2\mu E(1-\mu)}$$

$$c_{w0} = -3(1-\mu)$$

$$c_{w1} = \frac{c_{w0}}{h_m + \left(4 - \frac{1}{1-2\mu}\right) h_m}$$

$$S_{uw} = \frac{-4\mu(c_{uw} h_m + c_{w0})^2}{c_{uw} h_m^2 (1-\mu)}$$

$$\epsilon_{uw} = \frac{\ln\left(\frac{\epsilon_{uw} + \frac{\epsilon_{uw}}{2}}{\epsilon_{uw} \cdot \frac{\epsilon_{uw}}{2}}\right) \cdot \ln(-h_m(c_{uw} h_m + c_{w0}) - \ln(h_m B^2)}{2 \ln \frac{\epsilon_{uw}}{h_m}}$$
where $r_i$ represents the radius of the abnormal pressure zone (m), $\Delta P_n$ represents the formation pore pressure difference between the abnormal and normal pressure zones (MPa), $h_o$ represents the formation thickness of the oil reservoir (m), $B$ represents the radial position coefficients of lateral displacement, and $z_{ml}$ denotes the relative height (m).

Notably, the aforementioned thickness is not the production thickness of a single well but the sum of all of the formation thicknesses that can cause a change in pore pressure in the entire longitudinal development sequence. Therefore, in addition to the abundance of sandstone beds, there are numerous formations of varying permeability, barely permeable mudstone intercalations, and intervals within the depth range. As long as it is used for exploration, sandstone layers with a certain seepage capacity are affected by pore pressure to produce stress and strain. However, in the actual formation, a significant number of mudstone interlayers and intervals in the oil layer slightly change in volume owing to the change in pore pressure. To simplify the model, the influence of mudstone layers is ignored, and all vertical oil layers are integrated into an equally thick and horizontal oil layer. The converted thickness of the integration should be equal to the total thickness of all of the sandstones used for exploration.

According to the geometric equation and eq 1 in the cylindrical coordinate system, the formation stress of the upper reservoir after the formation of the regional pressure difference can be obtained as follows:

$$
\sigma_r = \frac{E}{(1 + \mu)(1 - 2 \mu)} \left[ 1 + 2(1 - \mu) (c_{w} h_{m} + c_{w0}) r^2 \right] 
$$

$$
\sigma_\theta = \frac{E}{(1 + \mu)(1 - 2 \mu)} \left[ 1 + 2(1 - \mu) (c_{w} h_{m} + c_{w0}) r^2 + 1 \right] 
$$

$$
\sigma_z = \frac{E}{(1 + \mu)(1 - 2 \mu)} \left[ 2 \mu (1 + c_{w0} r^2) c_{w} c_{z_{ml}} \right] 
$$

$$
\tau_{fr} = \frac{E}{2(1 + \mu)} \left( 1 + \mu \sigma_z m_{w} \right) c_{w} c_{z_{ml}} 
$$

where

$$
e_i = \exp[S_{z_{ml}} c_{w} h_{m} + (c_{w} h_{m} + c_{w0}) r^2] 
$$

and $\sigma_r$, $\sigma_\theta$, and $\sigma_z$ denote the radial, circumferential, and vertical stress, respectively (MPa), $\tau_{fr}$ is the shear stress (MPa), $c_e$ is the formation stress coefficient, $E$ is the formation elastic model (MPa), and $\mu$ is the formation Poisson ratio.

The increase in regional pressure difference increases the degree of uneven vertical deformation of the reservoir that forces the overburden stress to accumulate gradually, and the horizontal shear stress at the weak surface of the structure is the first to reach its crack limit and form faults. At the weak surface of the structure, the depth of the standard layer is first determined, subsequently introduced into eq 13, and finally resolved. The shear stress of the overburden is expressed as follows:

$$
\tau_{fr} = \frac{E}{2(1 + \mu)} \left( 4 \mu (c_{w} h_{m} + c_{w0})^2 (1 - \mu) c_{w1} - 4 \mu (c_{w} h_{m} + c_{w0})^2 - r_c \right) 
$$

where $h_l$ denotes the height of the weak horizontal structural plane fracture from the oil layer (m).

Similarly, the vertical normal stress at the crack of the weak horizontal structural surface can be expressed as follows:

$$
\sigma_z = \frac{E}{(1 + \mu)(1 - 2 \mu)} \left[ 2 \mu (1 + c_{w0} r^2) (h_o + h_l) c_{w} c_{z_{ml}} \right] 
$$

### 2.2. Calculation Model for Sectional Deformation of the Weak Structural Surface after Water Inflow

**Considering Stick–Slip.** In cases of the weak structural surface slip, the shear stress at each point of the horizontal fracture surface is different. There is a position where the shear stress is the highest, and this position first reaches the failure limit. When a point on the surface exceeds the maximum static friction, the shear stress is released immediately and slipping occurs. After sliding, the shear stress at this point decreases rapidly up to the maximum dynamic friction stress. Meanwhile, fracture sliding occurs immediately at this position and causes the adjacent position to slide. When the critical position is driven by the slip point, the shear stress of the part exceeding the maximum dynamic friction stress is released to form the slip. Assuming that the change value of slip is linearly related to the decrease in friction, the slip value of the formation with friction is expressed as follows:

$$
u_{sl}(r) = \frac{\nu_{sl0}(r) - \nu_{sl0}(r) \tau_{fr}(r)}{\tau_{fr}(r)} 
$$

where $\nu_{sl}$ represents the interlayer slip of the weak structural surface (mm), $\nu_{sl0}$ denotes the relative slip on the weak structural surface without friction (mm), $\tau_{fr}(r)$ represents the distribution function of the residual shear stress on the fracture surface of the weak horizontal structural surface (MPa), and $\tau_{fr0}(r)$ denotes the shear stress distribution of the critical interface, assuming that the weak horizontal structural surface has no slips (MPa).

The interfacial shear stress distribution function when the weak horizontal structural surface does not slip is calculated as expressed in eq 15. The relative slip on the weak horizontal structural surface under the frictionless condition can be approximately calculated according to the shear stress and the shear modulus of the weak structural surface before the surface crack as follows:

$$
u_{sl0} = G \tau_{fr1} \tau_{fr1} + h_l 
$$

where $G$ denotes the shear modulus of the weak horizontal structural surface (MPa) and $h_l$ represents the vertical distance between the weak horizontal structural surface and the oil-bearing formation (m).

According to the sliding weakening theory and considering the influence of the sliding weakening distance, the critical position stress is not completely released; thus, the residual shear stress on this weak surface is expressed as follows:

$$
\tau_{fr0}(r) = \tau_{fr} - (\tau_{fr} - \tau_{fr0}) \frac{\nu_{sl0}(r)}{D} 
$$

where $D$ denotes the sliding weakening range (m), $\tau_{fr}$ represents the maximum static friction stress of the weak
horizontal structural surface (MPa), and \( \tau_i \) represents the maximum dynamic friction stress of the weak horizontal structural surface (MPa).

Subsequently, the shear stress on the weak horizontal structural surface decreases from \( \tau_{0w} \) to \( \tau_w \), and the resulting slip is \( u_0 \). After the release of the shear stress, part of it is converted into the slip of the crack surface and the remaining part is distributed to the surrounding formation. In the process of gradual accumulation of residual shear stress in the adjacent position, the original shear stress distribution trend continues, and the increase in residual shear stress changes as follows:

\[
\Delta \tau_i(r) = \frac{\tau_{0w}(r) \int_0^\infty \left[ \tau_{0w}(t) - \tau_w(t) - \frac{w(t)}{\tau_i} \right] dt}{\int_0^\infty \frac{w(t)}{\tau_i} dt}
\]

(20)

where \( \Delta \tau_i(t) \) represents the increase in residual shear stress on the weak horizontal structural surface (MPa), \( u(t) \) denotes the slip on the weak horizontal structural surface (m), \( \Delta p_r \) is the formation pressure difference between regions (MPa), \( \tau_{0w}(t) \) is the shear stress before fracture on the weak structural surface (MPa), and \( \tau_i(t) \) is the residual shear stress on the fracture surface on the weak structural surface (MPa).

According to Amontons’ theorem, the dynamic and static friction stresses in the process of formation sliding are, respectively, expressed as follows:

\[
\frac{\tau_i}{\sigma_n} = \mu_{f_i}, \quad \frac{\tau_p}{\sigma_n} = \mu_{f_p}
\]

(21)

where \( \mu_{f_i} \) represents the dynamic friction coefficient of the weak horizontal structure, \( \mu_{f_p} \) denotes the static friction coefficient of the weak horizontal structural surface, and \( \sigma_n \) denotes normal stress on the weak horizontal structural surface (MPa).

Weak horizontal structural surface formation is not the production layer. The water in that layer is often caused by mistaking injection. The injecting water was planned to inject into production layers; however, for some reasons, the water run into the weak horizontal structural surface. There are three main water inflow ways of the horizontal surface: (1) Damaged injection well casing in the weak horizontal structural surface (the water that should have been injected into the reservoir flows into the weak surface), (2) incomplete scrapping of casing-damaged wells on the weak surface (the fluids from high-pressure reservoirs flow upward from the well to the weak surface and enters it through the damaged casing), and (3) poor cementing quality of the injection well. The fluids from high-pressure reservoirs flow upward from the incomplete cement zone to the weak surface. After the inflow of water into the weak horizontal structural surface, the invading water at the weak structural interface shares part of the overburden pressure. Therefore, the normal stress on the weak structural surface is no longer just the original overburden pressure, and its change is expressed as follows:

\[
\sigma_n = \sigma_n|_{z=0} + p_w - p_w
\]

(22)

where \( p_w \) denotes the inlet pressure of the weak horizontal structural surface (MPa).

The flooded rock and mineral surfaces were wetted using intrusive water. Water can excite the internal particles of the rock, and an unstable stick–slip occurs on the weak horizontal structural surface. After the rock surface is wetted, both the dynamic and static friction coefficients decrease.\(^{34}\) After the weak horizontal structural surface is flooded with water, the dynamic friction coefficient of the fracture surface can be expressed as follows:

\[
\mu_{f_i} = \eta \mu_{f_0} \quad \text{and} \quad \mu_{f_p} = \eta \mu_{f_0}
\]

(23)

where \( \mu_{f_0} \) denotes the dynamic friction coefficient of the nonwetting weak horizontal structural surface, \( \mu_{f_0} \) denotes the static friction coefficient of the nonwetting weak horizontal structural surface, and \( \eta \) represents the friction decrease coefficient of the weak horizontal structural surface after water inflow. The water inflow on the crack surface reduces the vertical stress, which mainly affects the static and dynamic friction of the surface.

When one point of the weak horizontal structural surface exceeds its maximum static friction stress, the surface begins to slip. The shear stress at the slip position of the crack surface was gradually released and it was borne by the adjacent position, which led to the stress at the adjacent position to be gradually greater than the maximum static friction stress, and the slip range gradually increased. The process of shear stress release on the crack surface is also a process of formation slip. The crack slip of a weak structural surface causes the formation static state to break, and the formation slip stops only when the shear stress at each position is less than the maximum dynamic friction stress. When the formation stops sliding, the forces at the two ends of the slip range are at the critical values of slip formation, and the shear stress on the positive surface is the maximum dynamic friction. According to this condition, the relationship between the critical slip positions at both ends can be expressed as follows:

\[
\begin{aligned}
\tau_i(r) &= \mu_{f_i} \sigma_n = 0 \\
\tau_p(r) &= \mu_{f_p} \sigma_n = 0
\end{aligned}
\]

(24)

where \( r_a \) and \( r_b \) represent the two critical slip positions of the weak horizontal structural surface (m).

In the actual calculation, \( r_a \) and \( r_b \) values need to be determined and solved using the iterative method. The slip weakening distance of the formation can be calculated according to the critical slip positions at both ends as follows:

\[
D_c = r_a - r_b
\]

(25)

When the highest shear stress on the surface exceeds the maximum static friction stress that can accumulate on the surface, a crack slip occurs immediately. By combining eqs 17, 19, 20, 24, and 25, the slip amount \( \tau_{0w}(r) \) at each point on the weak horizontal structural surface and the surface shear stress \( \tau_{0w}(r) \) after the slip can be obtained. The accumulation time of shear stress on the crack surface was very long, whereas the release time of the shear stress on the surface was very short. The shear stress release slip process on a crack surface is an iterative process. First, assume a small value of \( \Delta r \) \( r_a \) and \( r_b \) are both \( \Delta r \) as the step gradually increases from zero. Second, perform the iterative calculations according to the order of eqs 25, 19, 20, and 17 until \( r_a \) or \( r_b \) meets the condition of eq 18, and at this point, a step is suspended in the direction of the increase. The above iterative process is repeated until both \( r_a \) and \( r_b \) satisfy eq 18. Thereafter, the calculation stops, and the formation slip amount and distribution of residual shear stress
on the weak horizontal structural surface are obtained. As the monotonicity of each parameter in the iterative process is good, the convergence of iterative calculation is also good, and it is easy to meet the calculation accuracy. The initial condition of the model is the condition obtained by a trial calculation to find that the shear stress at each point on the crack surface reaches its maximum surface friction value. The boundary condition directly continues the shear stress distribution on the crack surface of eq 19 after trial calculation, which is radially infinite.

After the first crack slip of the weak horizontal structural surface is completed, with a gradual increase in the pressure difference between regions, the shear stress on the horizontal fracture surface continues to accumulate until the shear stress at a certain point on the surface equals the static friction stress of the surface and the formation slips again, presenting an intermittent slip. As the pressure difference between adjacent areas gradually increased, the shear stress on the crack surface of the formation accumulated, was released, reaccumulated, and was again released sequentially. Interestingly, the fracture surface appeared to slip, stop, reslip, and restop sequentially. The above phenomenon is essentially the stick–slip deformation phenomenon. According to the slip characteristics of the weak horizontal structural surface, it is necessary to calculate the regional pressure difference, shear stress, and slip distribution of the subsequent slip according to the slip amount and friction before and after each slip.

After the first slip of the weak horizontal structural surface owing to the increase in pressure difference between regions, the distribution of residual shear stress can be obtained using the above iterative method. The subsequent stick–slip deformation period can be divided into two stages: the stress accumulation and formation slip stages. In the stress accumulation stage, the distribution of residual shear stress in the last slip stage can be used to calculate the variation in the pressure between regions when the fracture surface meets the critical slip condition by combining eqs 15 and 21; thereafter, the distribution of residual shear stress in the subsequent slip can be obtained. This slip stage is similar to the initial slip stage, and the residual stress and slip amount were calculated using an iterative algorithm.

3. RESULTS AND DISCUSSION

To apply the aforementioned research methods in solving practical problems, a program for calculating the stick–slip deformation of a horizontal crack surface under different conditions was compiled using Visual Basic 6.0. Using the aforementioned program, the values of the intermediate variables could be obtained according to the given conditions, the stress equation of the slip surface could be obtained, and the relative slip amount and residual shear stress distribution of each slip of the weak horizontal structural surface could be calculated. Taking the average formation parameters of the West Block of the Nan-1 development zone of the Daqing oilfield as an example, we conducted a study on the stick–slip deformation law of the weak horizontal structural surface. The corresponding geometric conditions and mechanical parameters of the target formation are listed in Table 1.

Under the influence of the formation pressure difference between adjacent regions, the stress on the crack surface at the upper part of the reservoir increased. The expressions of vertical and shear stresses on the crack surface under the influence of pressure difference between the adjacent regions were obtained as follows:

\[
\tau_s(r) = -\Delta p_r \left(2.077 \times 10^{-3} r \exp(3.574 \times 10^{-2} - 3.982 \times 10^{-7} r^2) - 1.0247 \times 10^{-6} r^2\right)
\]

When the inter-regional formation pressure difference is 1.0 MPa, the vertical and shear stresses of the formation on the horizontal crack surface located at the upper part of the reservoir are as shown in Figure 2.

Under the influence of regional pressure difference, the vertical stress on the horizontal crack surface located in the upper part of the reservoir was lower than that caused by the gravity of the overlying formation. The maximum vertical stress generated by the pressure difference between the regions at 1 MPa was 1.499 MPa, 1070 m away from the center of the abnormal pressure zone. The maximum shear stress generated by the pressure difference between the regions was 1.581 MPa, and the distance from the center of the abnormal pressure zone was 871 m.

The vertical stress at the crack surface was produced by the pressure difference between the adjacent regions, along with the vertical stress produced by the overlying formation and subtraction of the pressure of the water inflow. According to eqs 21 and 23, the vertical stress was multiplied by the coefficient of dynamic friction to obtain the maximum dynamic friction that could be sustained by the position of the crack surface. Similarly, the vertical stress was multiplied by the coefficient of static friction to obtain the maximum static and dynamic friction that could be sustained at the crack surface position. Taking the maximum static friction stress that could be borne at different positions on the crack surface as an example, we analyzed the effect of variance in pressure on the crack surface before and after water inflow under different inlet pressure conditions. The results are shown in Figure 3.

The maximum static friction stress that the crack surface could sustain equaled the maximum shear stress that the crack surface could sustain before sliding. The lower the maximum static friction stress, the more prone the crack surface was to slipping. Meanwhile, the lower the maximum dynamic friction stress, the greater the shear stress released on the crack surface.
after the slip of the crack surface and the greater the slip degree of the crack surface. After water inflow, the reduction of static friction force on the crack surface will reduce the starting condition of formation slip. The maximum static friction stress that the crack surface could sustain before the water inflow was approximately 2 MPa. Once the crack surface was flooded, under the influence of wetting, even if the water inflow pressure was low, the maximum static friction stress value would be reduced to a substantial extent, making the crack surface more prone to slip. With an increase in the water inflow pressure, the maximum static friction stress gradually decreased, which further reduced the occurrence of slip on the crack surface. Similarly, the calculation formula of the maximum dynamic friction stress that the crack surface could sustain was similar to that of static friction stress, and its variation rule was the same as that of the static friction stress. Therefore, an increase in the water inflow pressure on the crack surface could reduce the slip limit and increase the slip degree.

By comparing the vertical normal and the maximum static friction stresses on the crack surface, the starting pressure difference between the adjacent zones could be determined through trial calculations, as shown in Figure 4, for the critical pressure difference between regions where the crack surface slippage occurred under different water inflow conditions. The trial calculations can be done by assuming a pressure difference \( \Delta p \) and calculating the vertical stress distribution and shear stress distribution in Figure 2. Then, the maximum static friction stress in Figure 3 was calculated according to the inflow pressure and vertical stress distribution by constantly assuming the pressure \( \Delta p \) until the two lines have just one focus, that is, the critical condition for slip.

The results of the pressure difference between the critical regions for interface slip under different water inflow conditions indicated that the condition for slip of the crack
surface without water inflow was that the pressure difference between the regions reaches 1.388 MPa. After the water inflow into the crack surface, the pressure difference between the regions required for the crack surface to slip gradually decreased to 1.1 MPa; thereafter, its value decreased continuously with an increase in the water inflow pressure. When the water inflow pressure reached 13.38 MPa, the starting pressure difference between the zones of fault surface sliding was 0, the pressure difference between the zones could immediately cause slip, and the formation had developed from stick−slip deformation to steady slip deformation. It can be observed that the process of water inlet pressure increase was also the process of the slip of the crack surface changing from stick to steady slip. The closer the crack surface was to the steady slip deformation, the lower the residual shear stress at the interface and the larger the cumulative slip on the crack surface.

The stick−slip deformation calculation program of the weak horizontal structural surface was used to calculate the shear stress distribution on the crack surface before and after the first slip when the water inflow pressure on the crack surface was 3 MPa. The results are shown in Figure 5.

According to the trial calculation, when the pressure difference between the zones reached 0.87 MPa, the shear stress of the formation exceeded the maximum static friction that the crack surface could sustain. At \( r = 871 \) m, the shear stress exceeded the maximum static friction stress sustained by the crack surface. At this point, the first slip of the stick−slip deformation began, and the shear stress on the crack surface was released, which was converted into a slip on the crack surface. During the slip process, the reduction in shear stress on the crack surface was shared among other positions, resulting in an increase in shear stress near the crack surface. When the residual shear stress at all positions on the crack surface was less than the maximum dynamic friction stress, the crack surface stopped sliding. Subsequently, with an increase in the pressure difference between regions, the residual shear stress on the crack surface continued to accumulate until the next slip position, forming a stick−slip deformation phenomenon.

Through calculation, the first fracture position \((r = 871 \text{ m})\) of the crack surface was plotted, as well as the shear stress of the horizontal crack surface and the slip amount of the interlayer under the effect of the pressure difference between regions. The slip deformation on the weak structural surface was calculated by eq 25, which was calculated in an iterative process, as shown in Figure 6.

From the first fracture position of the weak horizontal structural surface, the interlaminar shear stress increased linearly with the regional pressure difference and decreased immediately after reaching the interlaminar shear stress, forming a relative slip on the crack surface. After the first slip, residual shear stress occurred on the crack surface. As the pressure difference between the zones increased, the shear stress on the crack surface continued to accumulate. When it reached 0.98 MPa, the shear stress on the crack surface was greater than the maximum static friction stress, and a second slip was formed. The slip and stress accumulation processes were repeated such that the crack surface presented intermittent movement, forming the phenomenon of stick−slip. As the residual shear stress on the crack surface was different after each slip, the stick−slip period also changed.

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Figure 5. Shear stress distribution on the crack surface before and after the first slip.

Figure 6. Shear stress of the horizontal crack surface and the slip amount of the interlayer under the effect of the pressure difference between regions.
slightly. Figure 7 shows the corresponding relationship between the formation shear stress and regional pressure difference in the range $r$ from 0 to 3000 m.

After the first slip of the crack surface, the increment in the pressure difference between the zones required for formation slip was significantly reduced. As the formation became unstable, the differential pressure increment between the zones where each slip occurred changed. The distribution of residual shear stress after each slip was different, and it was difficult to determine its regularity.

After the initial slip formation, the distribution of residual shear stress on the crack surface changes, as shown in Figure 5. The area with high original shear stress is no longer the highest value, and the shear stress in the slip formation area decreases to varying degrees. The position of the slip condition was different each time, and the degree of shear stress release after each slip was also different. When the shear stress on the crack surface accumulates again, it will still increase according to the change rate before slip. In other words, in the process of long-term stick-slip deformation, the condition for the crack surface to begin to slip was uncertain. The change rate of shear stress on the crack surface during stress accumulation remains unchanged, although some of the crack surface will participate in the stress, and the position of the maximum formation slip is basically stable. In the stick-slip process, the amount of slip formed on the crack surface is shown in Figure 8, where the relationship between the slip amount of formation and the pressure difference between zones when $r$ varies from 0 to 3000 m is established.

The results demonstrated that the first slip of the crack surface was large, but the range was small. After the formation of the first slip, the range of the crack surface gradually increased during each slip. The maximum position of the slip was relatively stable and concentrated near $r = 870$ m. In other words, with the continuous formation of the slip, the slip range gradually expanded with an increase in inter-regional pressure difference, and the slip degree was the largest in the position where the slip was first formed.

Because the slip of the crack surface is a stick-slip deformation, after the formation of the first slip, the change in the pressure difference between the zones of the formation slips again decreases, and the slip range of the formation gradually expands. In the formation process of stick-slip deformation, slips initially occur in a continuous area, then the slip range gradually expands, and the slip degree gradually increases. After water inflow, the decrease of dynamic friction force will reduce the residual shear force after formation slip, release greater deformation, and increase the amount of

Figure 7. Shear stress on the crack surface under pressure difference between different zones.

Figure 8. Slippage of the crack surface under different pressure conditions.
formation slip. Therefore, when planning for shear casing damage induced by formation slip, a more strict range of pressure difference between safe zones should be implemented in areas where shear casing damage has occurred. In the area where the casing damage has occurred, once the pressure difference between the regions is not effectively controlled, the casing damage area easily expands again, thereby aggravating the extent of the casing damage in this area. The distribution of residual shear stress in the formation after stick-slip deformation is complex, and the condition for reforming slip is not met. Therefore, when drawing up the pressure difference between safe areas to prevent casing damage according to past experiences, it is necessary to consider that the slip conditions are not fixed in the old damaged areas as well as to select the pressure difference between the safe areas conservatively.

In addition, the water inflow pressure is a key factor affecting the formation slip. The water inflow pressure on the crack surface can significantly reduce the formation conditions to begin slipping and also reduce the residual amount of the maximum shear stress on the crack surface. This will lead to an increase in the release degree of the shear stress on the crack surface, resulting in a larger slip amount and range of the formation.

4. CONCLUSIONS

(1) For the horizontal crack surface formation without oil, the shear stress on the crack surface gradually accumulates under the influence of inter-regional formation pressure difference. When the shear stress exceeds the maximum static friction force that the surface can sustain, the shear stress on the crack surface is partially released, and a slip is formed. The shear stress after the crack surface slip was less than the maximum dynamic friction of the crack surface. With an increase in the pressure difference between the regions, the shear stress accumulates, and slip is also formed again. Therefore, the crack surface repeatedly exhibited a stick-slip deformation phenomenon.

(2) Under the influence of wetting, the maximum static friction stress of the crack surface is significantly reduced after the crack surface is flooded, making the crack surface more prone to slip.

(3) After the first slip of the crack surface, the pressure difference between the zones required for formation slip was significantly reduced. In the long-term stick-slip deformation process, the condition for the crack surface to slip is uncertain. With the continuous slip of the formation, the slip range of the formation gradually expands with an increase in the inter-regional pressure difference.

5. OILFIELD EXPERIMENT

The centralized damage depth range of casing in the horizontal crack surface of block X in Daqing oilfield from June 2008 to June 2013 was calculated. The average formation pressure at the initial stage of the formation of casing damage concentration area in this area is calculated. From June 2008 to June 2009, zone A was a low-pressure zone, with an average formation pressure of 10.01 MPa. Zone B and zone C were high-pressure zones, and the average formation pressures were 12.66 and 12.26 MPa, respectively. The interval pore pressure difference between zone A and zones B and C was 2.45 MPa, and the interval transverse distance is 1700 m. In oilfield production, it is generally considered that the casing damage is caused by the reduction of the casing diameter by 50 mm. On this basis, considering stick-slip and shear weakening, it is preliminarily calculated that the casing damage range of the horizontal crack surface in the two blocks is 773 m, which is consistent with the actually observed 790 m casing damage area (as shown in Figure 9).

In the initial casing damage area, some water injection wells were damaged, but they were not found and effectively controlled. Therefore, for a long time, a large amount of injected water has been wrongly injected, which gives a high water injection pressure to the crack surface. After the water enters the crack surface, the section sliding amount and sliding range of the crack surface further increase, and the critical pressure difference of section sliding decreases. The formation pressure and casing damage 4 years after the initial shear damage in block X were calculated.

After the formation of casing damage area in block X, the formation pore pressure was not well controlled, and the interval pore pressure difference was currently 1.58 MPa. Compared with the initial casing damage area, the subsequent casing damage area continues to expand, indicating that the formation slip increases due to the weakening of the crack surface slip after water entry. After the formation of casing damage in this block, although the regional differential pressure was artificially controlled and the regional differential pressure decreased by 0.87 MPa within 4 years, the water inflow in the crack surface was not effectively controlled, and the formation slip continued to increase. Through the test of three wells in this block during workover and drilling new wells, it was found that high-pressure water has been injected into the casing damage concentration area and the average water inlet pressure...
was 3.2 MPa. In this paper, the formation slip calculation method without considering stick–slip and shear weakening was used to calculate that the casing damage range in the later stage of casing damage is 1831 m and that the actual statistical length of the casing damage area was 1780 m, which are similar. In addition, by comparing the casing damage data, it was found that for the non-casing damage wells in the casing damage area in the figure, the casing damage of the crack surface was generally found within the next 1–2 years or other forms of casing damage were formed on the upper part of the crack surface. In the casing damage area, there were almost no exceptions except for the non-casing damage of the crack surface in the wells near the fault, and the casing damage of the crack surface was found in the later elimination. It can be seen that compared with the damage of the crack surface shear casing from June 2008 to June 2009 and from June 2009 to June 2013, the inter-regional pressure difference of 2.45 MPa at the initial stage of casing damage forms a casing damage area with a length of 790 m, while after the water inflow into the crack surface was 3.2 MPa, only the inter-regional pressure difference of 1.58 MPa forms a casing damage area with a length of 1780 m. It shows that the water inflow in the crack surface releases the shear stress on the layer, reduces the formation slip condition, intensifies the slip degree, and expands the range of casing damage area.

■ AUTHOR INFORMATION

Corresponding Author
Fengjiao Wang — Laboratory of Enhanced Oil Recovery of Education Ministry, Northeast Petroleum University, Daqing 163318 Heilongjiang, China; orcid.org/0000-0001-8414-3049; Email: wangfengjiao@nepu.edu.cn

Authors
Chaoyang Hu — Laboratory of Enhanced Oil Recovery of Education Ministry, Northeast Petroleum University, Daqing 163318 Heilongjiang, China; orcid.org/0000-0002-0905-6356
Chi Ai — Laboratory of Enhanced Oil Recovery of Education Ministry, Northeast Petroleum University, Daqing 163318 Heilongjiang, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c03441

Notes
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