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أنماط من خسائر مائع الحفر على أساس آليات كسر نشر الكتل الصخرية

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الخلاصة

فقدان سائل الحفر في تكوين كسر يضع قيودا مشددة على استكشاف وتطوير موارد النفط والغاز. ومع ذلك، مع تكوين الكسور المعقدة، فإن الحكم على انتشار الكسر واختيار التكنولوجيا المناسبة للوقاية عملية ضرورية للوقاية من الخسارة. في هذه الورقة، استنادا إلى شروط انتشار الكسور المختلفة التي تحدث، تم إنشاء نمط فقدان لمجموعة تشنغ زهنزهو (ZZC المجموعة) في حوض سيتشوان. تم تقسيم الخسائر في عمليات الحفر إلى خمس مراحل وتمت مناقشة القوانين لانتشار الكسر وخصائص الخسارة. باستخدام أساليب التحليل نفسها، والنظر في مجموعة من نسب الضغط الرئيسي الرأسي إلى الحد الأدنى من الضغط الأفقي، تم إنشاء أربعة أنماط خسارة في تشكيل كسور. هناك: النوع الأول، النوع الثاني، النوع الثالث، والنوع الرابع. من خلال تلخيص المزايا والشروط التي تنطبق على أساليب منع فقدان شيوعا، وثمانية اجراءات الوقاية يمكن أن تستخدم في مراحل مختلفة من الخسارة. وتقدم هذه الدراسة التوجيه النظري لمنع الخسائر والسيطرة على الضرر تشكيل.

Patterns of drilling fluid losses based on fracture propagation mechanisms of rock mass

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ABSTRACT

Loss of drilling fluid in fracture formation severely restricts the exploration and development of oil and gas resources. However, for formations with complex fractures, judgment of fracture propagation and choice of appropriate prevention technology are essential for prevention of loss. In this paper, based on the conditions for fracture propagation of different fractures occurring, a loss pattern of Zhenzhuchong Group (ZZC Group) in Sichuan Basin was established. The losses in the drilling processes were divided into five stages and the laws for fracture propagation and loss features were discussed. Using the same analysis methods and considering the range of ratios of vertical principal stress to minimum horizontal stress, four loss patterns were established in the formation of fractures. These are: type I, type II, type III, and type IV. By summing up the features and the conditions applicable for commonly used loss prevention techniques, eight prevention measures can be used in different stages of loss. This study provides a theoretical guidance for prevention loss and controlling the formation damage.

Keywords: Drilling fluid; fracture formation; fracture propagation; vertical fracture; lost circulation.

INTRODUCTION

With dwindling reserves of conventional oil and gas, the exploration of oil and gas resources by fracturing is gaining a lot of attention. However, fluid losses can occur during the process of drilling for fracturing reservoirs, which seriously affect the normal drilling work. Earlier, researchers carried out several studies to solve this problem and achieved substantial success.

Diagnosing factors that cause losses is a prerequisite for controlling the losses. Fractures and voids provide a channel for the loss of the fluids; positive pressure being its driving force (Zeng, 2001). According to loss data, Dyke *et al.* (1995) and Beda & Carugo (2001) proposed an efficient way to judge the fluid loss type, were to sum up the characteristic curves of different loss types. Ali *et al.* summed up the loss mechanisms and characteristics of pores, natural fractures, and induced fractures and concluded that there was no general way to diagnose a loss and that the diagnostic methods should consider rock mechanics, fracture properties, and solid particle designs of drilling fluids, etc. to establish the decision tree, and then select an effective control technology for loss (Ali *et al*., 2014; Pordel *et al*., 2014).

Prediction of fracture width is the key to preventing fluid loss. Lietard *et al.* (1996) developed a model based on Darcy's law, according to which, under laminar flow conditions, the plastic fluid flowing through fractures would result in a drop in the pressure. Based on this, they established an equation for predicting the dynamic fracture width (Lietard *et al*., 1996). Sanfilippo *et al.* (1997) and Lavrov (2006) used diffusion equation to derive a model for fracture loss, by considering the drilling parameters (e.g., duration of loss, loss volume, positive pressure, and plastic viscosity of the drilling fluid). Wang *et al* (2008a) developed a model to calculate the length and width of the induced fractures, brought out by the fracturing of rocks.. Tran *et al.* (2013) established a mathematical model for a single vertical fracture, and analyzed the relationship between fracture width and temperature difference, heat transfer time, and properties of the drilling fluid filtrate.

The tight sandstone gas reservoir of Jiulong mountainous field in Sichuan Basin has been chosen for this study. Based on propagation mechanism of the fracture, under three main stress conditions, the critical positive pressure of fracture propagation and the features of the losses of the drilling fluid, have been analyzed in this paper. Four loss patterns have been established, based on the range of ratio of vertical principal stress to minimum horizontal stress. In case of severe loss at each stage, eight kinds of loss control techniques can be chosen to prevent it.

GEOLOGICAL CHARACTERISTICS AND LOSS PROBLEMS

Jiulong Mountain field is located in the northern part of northwest Sichuan Basin. Zhenzhuchong (ZZC) Group is the main reservoir in this field. In this group, the maximum horizontal principal stress is the highest (79.5 MPa), followed by vertical principal stress (69.0 MPa), and then by the minimum horizontal principal stress (60.0 MPa). Moreover, ZZC Group is characterized with multiple pay zones, multiple pressure systems, and abnormal high pressure. The coefficient of pressure of ZZC Group ranges from 1.36 to 1.67, increasing along with the growth of burial depth.

Small-scale reverse fault is created in this field. The extent of the length of the fault is 2 to 17 kilometers, whereas the displacement of the fault is 10 to 100 m. As shown in Figure 1, statistical data shows that fractures of ZZC Group mainly include horizontal fractures, low angle fractures, high angle fractures, and vertical fractures, with percentages of 60.8%, 20.3%, 12.7%, 6.2%, respectively. The fractures have a length of 1.4 to 4.2 m, a hydraulic width of 5.9 to 261.4 μm and a linear density of 1.4 to 4.7 per meter.

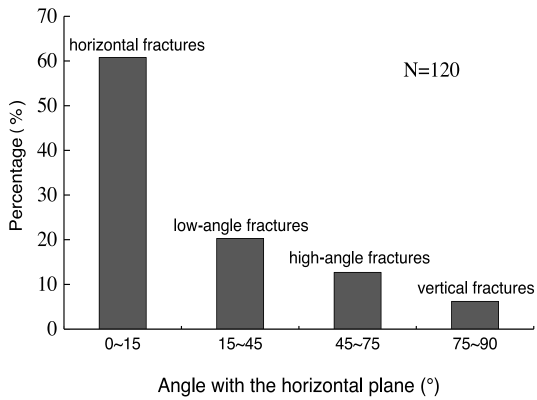

Fig. 1. Statistics of the occurrences of fractures of ZZC Group

The extent of loss mainly depends on the development of fracture, sealing performance of drilling fluid, and positive pressure (Xu *et al*., 1997; Li *et al*., 2007). Once there is a loss of drilling fluid in the tight gas reservoir, the productivity of the well gets affected. As shown in Figure 2, some wells with serious losses only produce small amounts of gas or even no gas in ZZC Group.

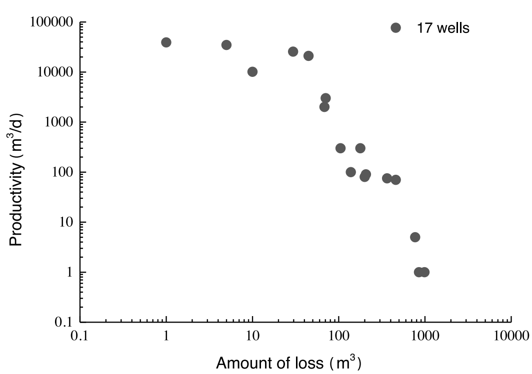

Fig. 2. Correlation between the loss of amount and gas productivity in ZZC Group

Prediction of the range of fracture width is essential for prevention of loss. However, judgment of the kind of fracture propagation that has occurred is the key for calculation of fracture width. Therefore, a relationship between fracture propagation and the wellbore fluid pressure should be found out.

RELATIONSHIP BETWEEN THE FRACTURE PROPAGATION AND PRESSURE OF WELLBORE FLUID

Lengthwise propagation of fracture is closely related to the normal stress loaded on the fracture surface. If the pressure of the wellbore fluid overcomes the normal stress of the fracture surface, the fracture opens. So, for a fracture of any angle, as shown in Figure 3, the normal stress σ_i (i = h, v, H-A and L-A, which denote the normal stress for horizontal fracture, vertical fracture, high angle fracture, and low angle fracture, respectively) is the resultant force due to vertical stress σ_v and minimum horizontal principal stress σ_h, in the normal direction on the fracture surface. It can be calculated by Equation (1):

$$\sigma_N = \sigma_v \cos\theta + \sigma_h \sin\theta \tag{1}$$

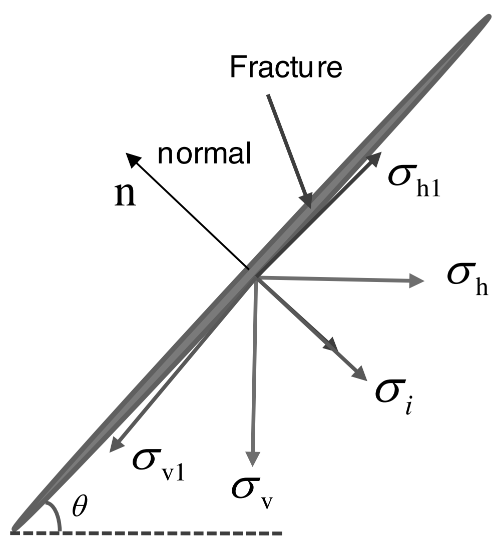

Fig. 3. Diagram for analysis of stress on fracture surface

If the pressure of the wellbore fluid exceeds the bearing pressure of fracture, the fracture will extend length wise (Dupriest, 2005; Salehi & Nygaard, 2012). This pressure is the fracture propagation pressure, which is equal to the sum of normal stress and tensile strength, and can be obtained by calculating Equations (2) to (5). For the vertical fracture, the pressure for fracture propagation is sum of the minimum horizontal stress and tensile strength of the rock (Rock has a tensile strength of 3 MPa).

$$P_V = \sigma_h + \sigma_t \tag{2}$$

Similarly, the propagation pressure of horizontal fracture is:

$$P_{\mathrm{H}} = \sigma_{\mathrm{v}} + \sigma_{\mathrm{t}} \tag{3}$$

The propagation pressure of low angle fracture is:

$$P_{\mathrm{L\text{-}A}} = \sigma_{\mathrm{L\text{-}A}} + \sigma_{\mathrm{t}} \tag{4}$$

The propagation pressure of high angle fracture is:

$$P_{\mathrm{H\text{-}A}} = \sigma_{\mathrm{H\text{-}A}} + \sigma_{\mathrm{t}} \tag{5}$$

Calculations using the above formula show that the pressure for propagation of horizontal fracture is 69 to 82 MPa, pressure for propagation of low angle fracture is 83 to 91 MPa, pressure for propagation of high angle fracture is 75 to 90 MPa, and pressure for propagation of vertical fracture is 60 to 75 MPa (Liu & Luo, 2004; Zhao *et al*., 2010). The order of opening up of fractures is in the following order: vertical fractures, horizontal fractures, high angle fractures, and low angle fractures with increase in positive pressure. Hence, as shown in Figure 4, based on the pressure for fracture propagation and range of wellbore fluid pressure, the loss patterns of ZZC Group can be said to have the following five stages.

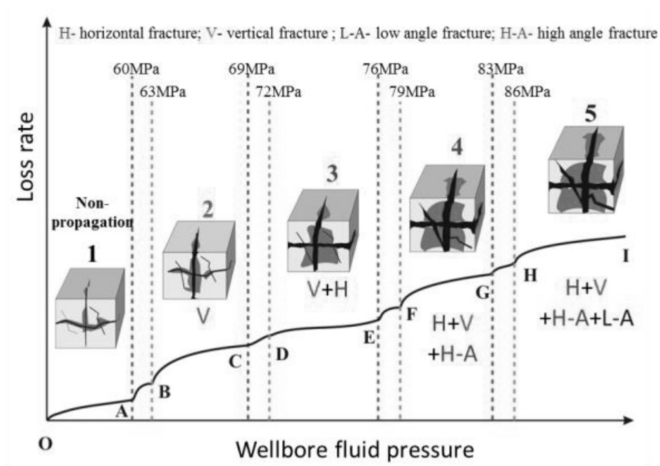

Fig. 4. Relation between the loss rate and wellbore fluid pressure in ZZC Group

The first stage (OA): Non-propagation loss. When the pressure in the wellbore is less than the minimum horizontal stress (60 MPa), propagation of the fracture does not occur. Loss occurs mainly in dissolved pores, caverns, or natural fractures. The loss rates are generally lesser, and easier to be controlled. This type of loss occurs most frequently in the drilling and cementing processes. For instance, L116-x2 well lost drilling fluid at 3138 - 3154 m, when the pressure in the wellbore was 47 MPa. The rate of loss was 3 m^3/ h and the cumulative amount of loss was 67.9 m^3.

The second stage (AC): This involves loss due to propagation of vertical fracture. As the pressure of wellbore fluid exceeds 60 MPa, the width of the vertical fractures increases (AB). If wellbore fluid pressure exceeds 63 MPa, vertical fractures extend in length (AB). Loss rate increases significantly and makes it difficult to control at this stage. The loss occurs most frequently in drilling and cementing processes. For example, the loss in case of L002-15-x2 well, occurred at 3880 m. When the pressure of the wellbore fluid was 61 MPa, the loss rate was 21.8 m^3/ h and the cumulative amount of loss was 68.3 m^3.

The third stage (CE): This involves loss due to vertical and horizontal propagation of fractures. When the pressure of the wellbore fluid exceeds 69 MPa (vertical principal stress), the width of horizontal fracture increases (CD). On exceeding 72 MPa, the horizontal fractures extend in length (DE). Increase in loss rate is small and makes it difficult to control at this stage. This type of loss occurs occasionally in the cementing process. For example, this loss occurred in the L002-7 well, during the cementing process of ZZC Group formation. When the pressure of the wellbore fluid was 70 MPa, the loss rate was 30 m^3/ h. The cumulative amount of loss of cement slurry was 64.8 m^3.

The fourth stage (EG): This involves the loss due to propagation of vertical fractures, horizontal fractures, and high angle fractures. When the pressure of wellbore fluid exceeds 76 MPa ($\sigma_{NH\text{-}A}$), width of the high angle fracture increases (EF). When it reaches 79 MPa, high angle fractures extend in length (FG). Loss rate is only smaller than the AC segment, and also makes it difficult to control at this stage. This loss occurs only in special operations. For example, the L002-4-x2 well formed in lifting sand process with drilling fluid having high density of 2.30 g/ cm^3. When the pressure in the wellbore fluid was 81 MPa, loss rate was 76.5 m^3/ h. The cumulative amount of loss of drilling fluid was 44.7 m^3.

The fifth stage (GI): This involves loss due to propagation of vertical fractures, horizontal fractures, high angle fractures, and low angle fractures. When the pressure of the wellbore fluid exceeds 83 MPa ($\sigma_{NL\text{-}A}$), width of low angle fractures increases (GH). When it reaches 86 MPa, low angle fractures extend in length (HI). Loss rate is smaller than the EG segment and makes it difficult to be controlled at this stage. Loss does not occur during drilling process, but occurs during the hydraulic fracturing. For example, L105 well had a loss rate of 7.8 m^3/ min with a fluid pressure of 97 MPa during the hydraulic fracturing.

Based on the above analysis, loss mainly occurs in the first and second stages in ZZC Group. It can be seen that propagation of only vertical fractures occurs in the second stage. So, the width of the vertical fractures is an important parameter for designing the size of sealing materials under different positive pressures.

PATTERNS OF LOSS CONTROLLED BY VERTICAL STRESS AND THE MINIMUM HORIZONTAL STRESS

In fact, for any stress conditions in the ground, patterns for the loss of drilling fluid can be determined using above analysis method. The key is to compare the sizes of σ_N, σ_v, and σ_h. Setting $k = \sigma_v / \sigma_h$, the relative sizes of the three can be determined from the value of *k*.

As shown in Figure 5, statistics of the in-situ stress distribution in China show that σ_v is lower than σ_h in the shallow depths of formation, and σ_v is greater than σ_h for depths of more than 500 m. The range of *k* is calculated by the Equation (6) (Li & Qi,1988).

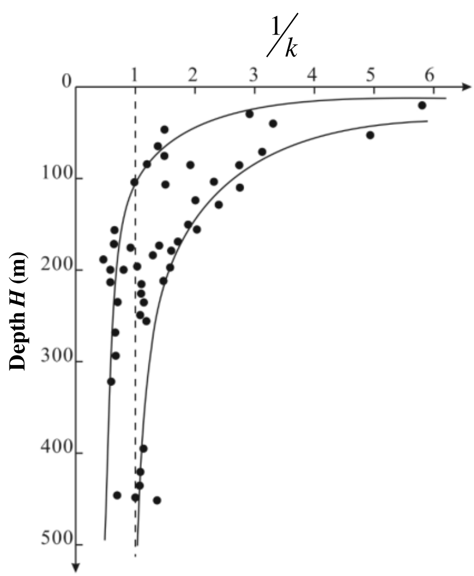

Fig. 5. Relationship between *k* and depth *H* in China (Li *et al.*, 1988)

$$128/H + 0.5 \leq \sigma_h / \sigma_v \leq 167/H + 1.10 \quad (6)$$

After calculation, *k* was found to be in the range of 0.3 to 2.0. Depending on the range of *k*, patterns for loss of drilling fluid are divided into the following four types:

Type I loss (0.3 < k ≤ 0.6): As shown in Figure 6, the sequence of opening of fractures is: horizontal fractures, low angle fractures, high angle fractures and vertical fractures. The loss may occur at the formation of the soft surface of extrusion-type or transitional basin (Li, 1982), whose vertical principal stress is the smallest and minimum horizontal principal stress is relatively larger. This phenomenon is common in the formation along with development of reverse faults. For example, this type of loss took place during the drilling process of the Quaternary formation of Red River Oilfield and Jinghe River Oilfield.

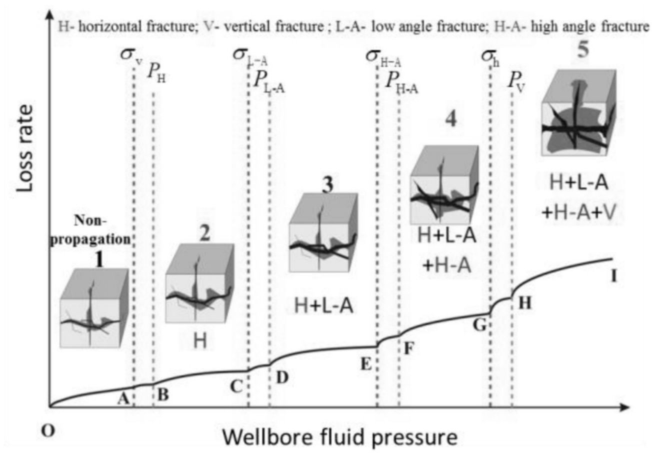

Fig. 6. Type I loss.

Type II loss (0.6 < k ≤ 1.0): As shown in Figure 7, the sequence of opening of fractures is: horizontal fractures, low angle fractures, vertical fractures, and high angle fractures. This loss may occur mainly at the formation of soft surface of extrusion-type or transitional basin, whose vertical principal stress is slightly less than the minimum horizontal principal stress. This phenomenon is common in the formation of reverse faults. For example, Triassic of Talimu basin encountered this type of loss in the drilling process (Li, 1982; Wang & Guan, 1997).

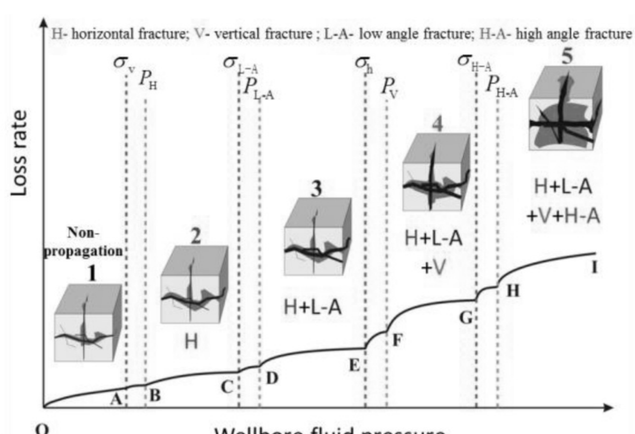

Fig. 7. Type II loss

Type III loss (1.0 < k ≤ 1.6): As shown in Figure 8, the sequence of opening of fractures is: vertical fractures, horizontal fractures, high angle fractures, and low angle fractures. This type of loss is most common in formation with strike-slip faults or normal faults, whose vertical principal stress is greater than the minimum horizontal principal stress. For example, this type of loss occurred during the drilling in the formation of ZZC Group.

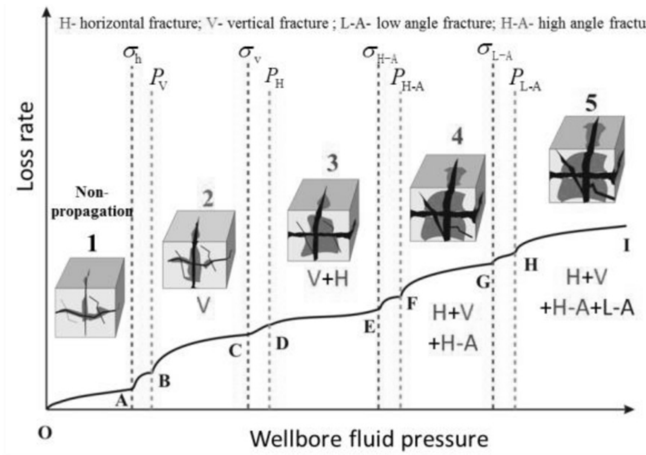

Fig. 8. Type III loss

Type IV loss (1.6 < k ≤ 2.0): As shown in Figure 9, the sequence of opening of fractures is: vertical fractures, high angle fractures, horizontal fractures, and low angle fractures. This type of loss is also common in formation with normal faults, whose vertical principal stress is slightly greater than the minimum horizontal principal stress. This type loss occurred in the process of drilling during the formation of XJH Group in Jiulong Mountain field.

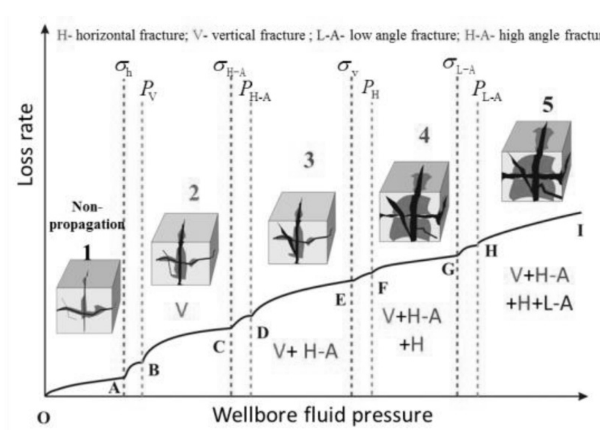

Fig. 9. Type IV loss

DISCUSSION

Based on the four loss patterns, fractures propagation law for different occurrences can be classified under different stress conditions. Amongst them, vertical fracture propagation should be particularly emphasized, since there is a maximum contact area between the vertical fractures and the borehole. If a point is broken perpendicularly, it may result in failure of the entire sealing zone, just in the same manner as that of the opening of zipper. So, if the vertical fractures propagate, loss rate would increase sharply.

It should be noted that this paper assumes that the direction of extension of fractures is the same as that of the maximum principal stress, and does not consider the impact of maximum horizontal principal stress. The formation may have natural fractures with an arbitrary angle to the direction of the maximum horizontal principal stress. The pressure for fracture propagation in this situation is difficult to determine, and is part of further study.

Severity of loss depends on the degree of fracture propagation. The fracture propagation is closely related to the rock strength, fracture length, and the pressure of wellbore fluid column. Depending on the severity of loss, different loss prevention techniques can be selected (Figure 10). Loss prevention techniques that are currently used, are as follows (Yang *et al*., 2005; Wang *et al*., 2007; Wang *et al*., 2008b; Liu *et al*., 2010): (1) *Underbalanced drilling*: It is mainly suited for loss of low pressure formation and has a high drilling speed. More importantly, this technique can effectively control the formation damage. It can be used for prevention of losses at the first and second stages. (2) *Plugging while drilling:* It is mainly suited for prevention of losses in the first stage, because the first stage generally has smaller loss rate than others, as well as a small difficulty in plugging. (3) *Bridge plugging*: The requirement is that the fracture width should not be too large and particle size gradation of bridging agents should be reasonable, and can be used for prevention of loss in the first to third stages. (4) *Chemical plugging*: The requirement is that mud density should be low, and can be used for prevention of loss in the first and second stages. (5) *Cement plugging*: The requirement is that the density of drilling fluids and cement slurry should be as close as possible, and the loss rate should be small, and can be used for prevention of losses in the first to third stages. (6) *Special gel plugging*: Source material is wide, but the operation process is very complicated. Because there is no limit to the fracture width, it can be used for prevention of loss in the third to fifth stages. (7) *Plugging with soft and hard plugs*: Since soft plug has a strong shear strength and friction resistance, it has a significant effect on induced losses for the fractures or caves, and can be used for prevention of losses in the third to fifth stages. (8) *Expansion pipe plugging*: It can effectively deal with the serious losses, with simple operation and at low cost, and can be used for controlling losses in the third to fifth stages.

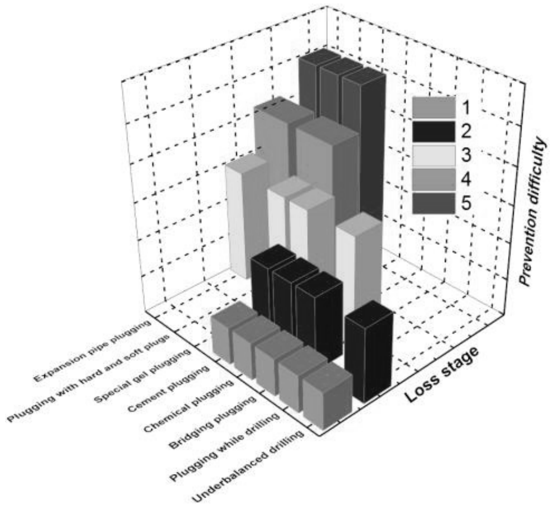

Fig. 10. Prevention technology in different loss stage

In case of serious losses, in order to achieve better sealing effect, several techniques are usually used in combination, and have their respective advantages in achieving rapid plugging effect, thereby increasing the success rate of plugging. For example, a method combining special gel and cement plugging technology, successfully handled a serious loss problem of Luojia 2 well (Wang *et al*., 2008b).

In summary, regardless of loss pattern, the more severe the fracture propagation, the more difficult the sealing is. Plugging process is also more complex from the first to the fifth stage. Therefore, prevention of loss should be done in the following way:

(1) Before drilling, pattern of loss and pressure for fracture propagation can be determined from the magnitude of stress, occurrences of fracture, rock strength. Based on the loss pattern and pressure for fracture propagation, the drilling fluid density can be adjusted, or a sealing material that matches with the width of the fracture can be prepared, to prevent the loss of drilling fluid.

(2) Using underbalanced or nearly balanced drilling technology if possible, to keep away losses from occurring or being at the non-propagation stage. Otherwise, the difficulty and cost for prevention of loss will increase.

(3) If the loss occurs in the reservoir section and is not serious, temporary sealing technology should be considered to control formation damage (Yan et al., 2012). After drilling, the sealing zone can be removed and fracture permeability recovered by flow-back, acid treatment, or other means.

CONCLUSION

(1) By comparing the pressures for fracture propagation of fractures occurring differently, loss pattern in ZZC Group was established and divided into five stages to analyze the characteristics of loss. Losses mainly occur in the first or second stage. Vertical fractures have the highest impact on loss of drilling fluid, although the percentage is minimal. Therefore, prevention of loss should focus on propagation of vertical fractures.

(2) Based on range of the ratio of vertical principal stress to minimum horizontal stress, four loss patterns, type I, type II, type III and type IV were established for any stress conditions in the ground to provide theoretical guidance for calculation of fracture width and sizes of sealing materials were determined.

(3) Techniques for prevention of conventional losses and conditions for application were summarized in the five stages. Eight techniques can be used to prevent losses in different stages. Moreover, in order to avoid losses and protect the reservoir, some measures should be adopted, such as underbalanced drilling and temporary sealing technology.

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