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Research article

A collapse pressure prediction model for horizontal shale gas wells with multiple weak planes

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Abstract

Since collapse of horizontal wellbore through long brittle shale interval is a major problem, the occurrence characteristics of weak planes were analyzed according to outcrop, core, and SEM and FMI data of shale rocks. A strength analysis method was developed for shale rocks with multiple weak planes based on weak-plane strength theory. An analysis was also conducted of the strength characteristics of shale rocks with uniform distribution of multiple weak planes. A collapse pressure prediction model for horizontal wells in shale formation with multiple weak planes was established, which takes into consideration the occurrence of each weak plane, wellbore stress condition, borehole azimuth, and in-situ stress azimuth. Finally, a case study of a horizontal shale gas well in southern Sichuan Basin was conducted. The results show that the intersection angle between the shale bedding plane and the structural fracture is generally large (nearly orthogonal); with the increase of weak plane number, the strength of rock mass declines sharply and is more heavily influenced by weak planes; when there are more than four weak planes, the rock strength tends to be isotropic and the whole strength of rock mass is greatly weakened, significantly increasing the risk of wellbore collapse. With the increase of weak plane number, the drilling fluid density (collapse pressure) to keep borehole stability goes up gradually. For instance, the collapse pressure is 1.04 g/cm^3 when there are no weak planes, and 1.55 g/cm^3 when there is one weak plane, and 1.84 g/cm^3 when there are two weak planes. The collapse pressure prediction model for horizontal wells proposed in this paper presented results in better agreement with those in actual situation. This model, more accurate and practical than traditional models, can effectively improve the accuracy of wellbore collapse pressure prediction of horizontal shale gas wells.

Keywords: Shale gas; Horizontal well; Bedding; Wellbore stability; Weak plane; Collapse pressure; Sichuan Basin; South

Key technologies in efficient development of shale gas are horizontal well drilling and staged volume fracturing. Since shale gas horizontal wells are mainly drilled through brittle shale reservoirs, wellbore instability is more serious in horizontal section drilling. Wellbore collapse or sloughing often result in hole enlargement, sticking, packing, and burial of drill pipes, etc. even abandonment of the whole well with huge economic losses [1−3]. In addition, wellbore instability brings big challenges to cementing and completion, affecting cementing quality, the staged fracturing before gas production, and finally the effectiveness of shale gas development. Due to abundant weak planes, such as bedding planes, cracks, and micro-fissures [3,4] in shale, shale is strongly heterogeneous in strength, so the prediction methods for conventional borehole stability are unable to guide drilling operation. Therefore, it is necessary to develop a more suitable prediction method for wellbore instability according to the characteristics of shale gas reservoirs.

In view of the borehole instability in strength anisotropic formations, a lot of researches have been carried out at home and abroad. Aadony [5,6], Dusseault [7], and Ong [8] et al. considered the effects of anisotropic bedding formation on stability of deviated wellbore, and studied the wellbore stability by using strength theory of weak plane. Jin [9,10], Liu [11], Yuan [12], and Lu [13,14] et al. examined the relationship between wellbore stability and the weak planes of vertical

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and deviated wells on the basis of linear elasticity mechanics model and weak plane strength theory. In view of borehole collapse in the testing of horizontal wells, Liu [15] established a calculation model for collapse volume of horizontal open-holes in multiple-weak-plane formation. However, the study on collapse pressure prediction of horizontal wells in shale with rich beddings and fractures is not deep, especially the wellbore stability problem in shale formation with multiple weak planes needs further investigation. Therefore, the occurrence characteristics of weak planes in shale were examined, the borehole stress distribution of horizontal wells was analyzed, and the strength characteristics of shale with multiple weak planes were studied on the basis of weak plane strength theory. The collapse pressure prediction model for horizontal wells in shale formations was proposed, and the solution to wellbore collapse instability was obtained.

1. Occurrence characteristics of weak planes in shale

Since shale is hard and brittle, rich in bedding, and complex in in-situ stress, a large number of weak planes are developed in shale formations, including structural fractures (tensional and shear fractures), lamellation seams, sliding seams, diagenetic contraction micro-fissures, and fractures caused by abnormal pressure during evolution of organic matter, which are different in geologic origins, identification characteristics and distribution patterns [16]. Therefore, shale outcrops, core samples, microstructure analysis data and imaging logging data were made use of jointly to find out the characteristics of weak planes in shale formations, especially the occurrence of weak planes. The results show that: ① there are abundant fissures in the shale crops, mostly horizontal bedding, horizontal fractures and vertical fractures (including joints); ② analysis of core samples of Longmaxi shale in Weiyuan district, Sichuan Basin, shows that there are horizontal fractures, bedding and vertical fractures (high angle fractures), and some oblique fractures in the shale samples, among them 51 vertical fractures accounting for 52.41% of the total, 33 horizontal fractures accounting for 33.67% of the total, and a few high and low angle fractures accounting for 9.18% and 5.10% of the total respectively, it can be seen that Longmaxi shale mainly has perpendicular or nearly vertical fractures; ③ Scanning Electron Microscopy (SEM) analysis results of shale samples show that the shale bedding planes are smooth, with micro-fissures parallel to the bedding; the shale sections are rough and rugged, with rich micro-pores and micro-fissures, but the occurrence of micro-fissures is stochastic, which makes shale easier to break up [16]; ④ the results of micro-resistivity scanning imaging logging (FMI) show that dynamic resistivity imaging can better identify bedding planes and tensile fractures, while static resistivity imaging can better identify fractures, but is poorer in detecting bedding planes; FMI logging data show that there are a large number of bedding and high-angle tensile fractures in shale formations.

It can be seen that weak planes in shale formations are mainly structural fractures, bedding and micro-fissures. Their development and occurrence characteristics are mainly affected by mineral composition, in-situ stress, lithology, sedimentary diagenesis, lithofacies, physical properties, and pore pressure, in which the mineral composition of the rock is more important. The minerals of Longmaxi shale include quartz (41.19%), carbonate (26.24%), and clay (37.33%). Longmaxi shale, which is pure, tight and brittle, has a large number of fractures developed under the long-term effect of in-situ stress. The fissures in shale formations are different in occurrence. Specifically, shale bedding, formed under sedimentary diagenesis, is composed of a series of nearly parallel bedding laminae; the bedding planes are weak in mechanical properties and easy to break up, and the occurrence of bedding is largely controlled by occurrence of formations. Structural fractures are formed due to local tectonism or are born with local tectonism; their occurrence is closely related to the formation and development of local structures, mostly perpendicular to bedding planes. Although stochastic somewhat in development, the formation of micro-fissures is mainly related to diagenetic contraction and abnormal pressure caused by organic matter evolution. Therefore, a large number of weak planes developed in shale formations have a special feature, i.e., most weak planes are large in crossing angle (close to orthogonal).

2. Strength characteristics of shale with weak planes

2.1. Strength theory of single group of weak planes

The strength theory of a group of weak planes proposed by Jaeger (1960) defined the shear failure condition of rock mass with one plane or a group of parallel weak planes [17]. As is shown in Fig. 1, there is a group of weak planes (*AB*) in the rock mass. Assuming the angle between *AB* plane's normal and the max. principal stress direction is β.

Thus, according to Mohr's stress circle theory and Coulomb criterion, the failure criterion of weak plane can be expressed as:

$$\sigma_1 = \sigma_3 + \frac{2(c_w + \sigma_3 \tan \varphi_w)}{(1 - \tan \varphi_w \cot \beta)\sin 2\beta} \quad (\beta_1 \le \beta \le \beta_2) \tag{1}$$

If Eq. (1) is not satisfied, rock body failure will occur:

$$\sigma_1 = \sigma_3 + \frac{2(c_0 + \sigma_3 \tan \varphi_0)}{(1 - \tan \varphi_0 \cot \beta_0)\sin 2\beta_0} \quad (\beta < \beta_1, \beta > \beta_1) \tag{2}$$

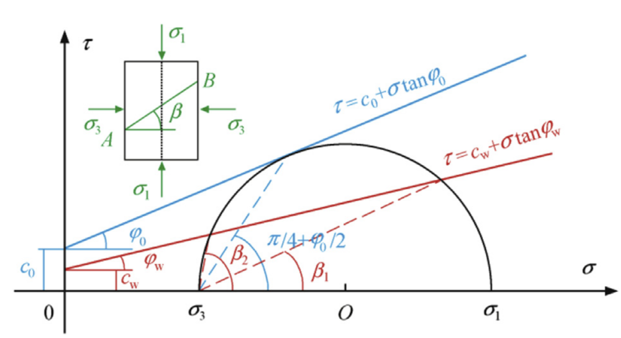

Fig. 1. Strength analysis curve of shale with one group of weak planes.