Prediction Method of Shear Wave Time Difference for Low Permeability Sandstone in Ledong Area of Yinggehai Basin

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Abstract

Low permeability sandstone reservoir is the key point of exploration and development in Ledong area of Yinggehai basin. Fine interpretation of P-and S-wave elastic wave velocity is the key to obtain dynamic rock mechanics parameters, but most wells in this area lack S-wave logging data. Based on this fact, this paper first uses the actual P-and S-wave data fitting method, and uses the P-and S-wave relationship in array acoustic logging, The S-wave prediction model is established according to lithology, and the S-wave time difference is calculated. Xu white model is used to quantitatively characterize the bulk modulus and shear modulus of low permeability sandstone matrix, dry rock bulk modulus and shear modulus, and then the shear wave velocity of rock is calculated by Gassmann formula. It is found that the S-wave prediction model established by fitting the measured P-wave and S-wave data is poor, and it is difficult to meet the requirements of the next exploration and development. The Xu white model is based on the density curve, shale content and other actual data, and is suitable for the complex lithology of the study area, with high prediction accuracy, Based on the Xu white model, a set of shear wave prediction method is established.

Keywords

Yinggehai Basin; S-wave Velocity Prediction; Low Permeability Sandstone; Xu White Model; Rock Mechanics Parameters.

1. Introduction

The widely developed low-permeability sandstone reservoir in Ledong area is of great significance for oil and gas exploration in this area [1], but the characteristics of rock mechanics parameters are unclear, which seriously affects the next exploration and development. Based on the actual situation of the study area, the rock mechanics parameters curve of well point is determined by using logging data, but it is difficult to accurately determine the rock mechanics parameters due to the lack of shear wave information in many areas. S-wave velocity information is the key to reservoir lithology, physical properties and fluid identification [2], and it is also the basic data in pre stack seismic inversion and pre stack seismic attribute analysis [3]. The accuracy of S-wave velocity information also affects the accuracy of oil and gas detection and reservoir seismic prediction. However, S-wave logging technology has not been widely used, so in the absence of S-wave data, It is particularly important to calculate S-wave velocity from P-wave data or other reservoir parameters [4]. In recent years, scholars at home and abroad have done a lot of work on the prediction of S-wave velocity. Castagna et al. [5] have given S-wave velocity prediction formulas under different lithological conditions. Greenberg et al. [6] have compared the P-wave velocity predicted by Gassmann formula with the measured P-wave velocity to reverse the S-wave velocity, Xu Shiyong et al. [7] obtained the shear wave velocity by fitting the measured P-and S-wave statistical relationship, and Robert et al.

[8] proposed using Xu white model to calculate the shear wave velocity; Guo Dong et al. [9] used Xu white model to calculate shear wave velocity, and then used logging curve correction to make the prediction result more accurate.

In view of the lack of S-wave velocity of logging data in most areas of the study area, a set of S-wave prediction model suitable for the study area based on Xu white model is established by using the fitting method of measured S-wave data and Xu white model method to compare and analyze the prediction results with the measured results, The results provide reliable data for the simulation of in-situ stress field and the optimal fracturing design of the target formation in this area. On the other hand, it provides a reference for the prediction of shear wave time difference in surrounding blocks.

2. Fitting model of measured P-wave and S-wave data

The measured S-wave data of Miocene Series in l10-5 well are collected, and the S-wave calculation model is fitted according to different lithology according to the measured S-wave data of Miocene Series in l10-5 well(1), (2):

$$\text{Sandstone: } \Delta t_s = 2.1999\Delta t_p - 34.832 \tag{1}$$

$$\text{Mudstone: } \Delta t_s = 2.4008\Delta t_p - 47.618 \tag{2}$$

Where: Δt_s is shear wave time difference, μs/ft; Δt_p is the time difference of P-wave, μs/ft.

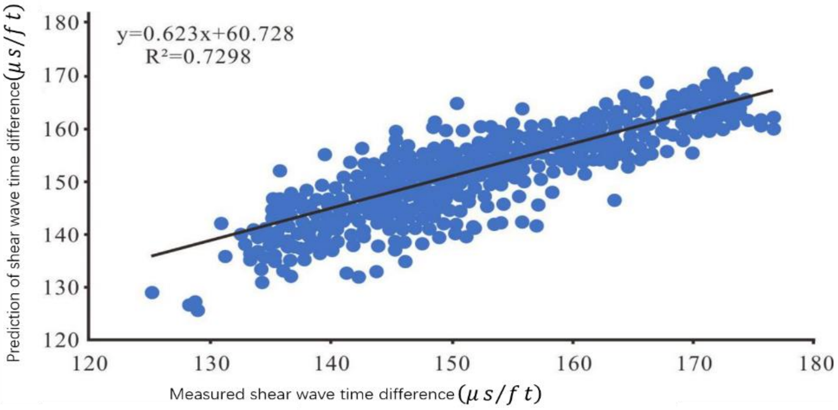

Fig. 1 Correlation diagram of measured shear wave time difference and predicted shear wave time difference

3. Xu-White Model

3.1 Continuous porosity prediction

Because of the complex lithology of the study area, the porosity is predicted by two kinds of lithology, and the measured P-wave time difference and core test data are used to fit the sandstone section. The mudstone section is calculated by the empirical formula proposed by Wyllie et al. [10], and modified according to the actual situation of the study area.

Porosity prediction model of sandstone section $(GR \leq 90API)$:

$$\phi = 0.234\Delta t_p - 16.2;\ R^2 = 0.8134 \tag{3}$$

Where: ϕ Is porosity %.

Prediction model of mudstone porosity $(90API < GR \leq 110API)$

$$\phi = \frac{\Delta t - \Delta t_m}{\Delta t_w - \Delta t_m} = \frac{\Delta t - 70}{130} \tag{4}$$

Where: Δt It is the acoustic logging value of mudstone, μs/ft;

Δt_m In the study area, 70 μs/ft is selected according to the acoustic transit time logging curve;

Δt_w pore fluid in mudstone is water 200 μs/ft.

3.2 Xu-White Prediction of model shear wave velocity

Robert et al. [8] thinks that the pore aspect ratio and porosity are the key to affect the shear wave velocity of sandstone and mudstone. It is also considered that the sand and argillaceous skeleton are composed of sand and mudstone particles. It is assumed that the pore aspect ratio in sandstone is significantly different from that in mudstone. Considering the pore division in argillaceous sandstone, the input parameters of Xu white model include the shale content The relationship among pore aspect ratio, porosity and matrix modulus of rock is considered.

The volume of mudstone is calculated by formula (5):

$$V'_{sh} = V_{sh}/(1-\varphi) \tag{5}$$

Where: V_{sh} is argillaceous content;

According to the time difference of P-wave and S-wave of sand and mudstone particles, the time difference of P-wave and S-wave of rock matrix and the density of rock matrix (6) ~ (10) are calculated by Wyllie equation [10]:

$$K_{rm} = \rho_{rm}\left[\frac{1}{(T_{rm}^{P})^2} - \frac{4}{3(T_{rm}^{s})^2}\right] \tag{6}$$

$$\mu_{rm} = \frac{\rho_{rm}}{(T_{rm}^{s})^2} \tag{7}$$

$$T_{rm}^{p} = (1-V'_{sh})T_{sa}^{p} + V'_{sh}T_{sh}^{p} \tag{8}$$

$$T_{rm}^{s} = (1-V'_{sh})T_{sa}^{s} + V'_{sh}T_{sh}^{s} \tag{9}$$

$$\rho_{rm} = (1-V'_{sh})\rho_{sa} + V'_{sh}\rho_{sh} \tag{10}$$

Where: K_{rm} and μ_{rm} are bulk modulus and shear modulus of rock matrix; T_{rm}^{p}, T_{rm}^{s}, ρ_{rm} They are the time difference of P-wave and S-wave and density of rock matrix; T_{sa}^{p} and T_{sa}^{s}, Which time difference of longitudinal and shear waves of sandstone matrix is respectively; T_{sh}^{p} and T_{sh}^{s}, Time difference of longitudinal and transverse waves in mudstone matrix; ρ_{sa} and ρ_{sh} are the density of sand and mudstone matrix;

Using Kuster toksoz equation [11] to build the dry rock skeleton model, combined with (DEM) differential equivalent theory, the elastic modulus of dry rock skeleton is obtained by cumulative superposition. Firstly, let F_1 and F_2 be functions of pore aspect ratio of sandstone matrix, where x is the pore aspect ratio of Sandstone Matrix and y is the pore aspect ratio of mudstone matrix. Then let (11) to (12) be as follows:

$$Z = -\frac{1}{3.5} \times \frac{K_{rm}}{3K_{rm}+4\mu_{rm}}[\varphi_{sa}F_1(x) + \varphi_{sh}F_1(y)] \tag{11}$$

$$T = -\frac{1}{30} \times \frac{\mu_{rm}}{3K_{rm}+4\mu_{rm}}[\varphi_{sa}F_2(x) + \varphi_{sh}F_2(y)] \tag{12}$$

Where: φ_{sa} is sandstone porosity; φ_{sh} is mudstone porosity.

The bulk modulus of rock matrix (K_{rm}) and shear modulus of rock matrix (μ_{rm}). The bulk modulus and shear modulus of dry rock are calculated as parameters.

$$K_{dr} = \frac{K_{rm}+4Z\mu_{rm}}{1-3Z} \tag{13}$$

$$\mu_{dr} = \mu_{rm} \times \frac{1+T(9K_{rm}+8\mu_{rm})}{1-6T(K_{rm}+2\mu_{rm})} \tag{14}$$

Where: K_{dr} is the bulk modulus of dry rock; μ_{dr} is the shear modulus of dry rock;

Combined with the actual velocity and modulus of the work area, the Gassmann formula [12] is expressed as (15) ~ (16) to characterize the relationship between shear wave velocity and dry rock modulus, so as to accurately obtain the shear wave velocity information.

$$\rho_b = (1-\varphi)\rho_{rm} + \varphi\rho_f \tag{15}$$

$$V_S(\text{forecast}) = \sqrt{\frac{\mu_{dr}}{\rho_b}} \tag{16}$$

Where: V_S is the shear wave velocity, ft/μs.

4. Time difference test of prediction S-wave

Using the two S-wave time difference prediction methods in this paper, the S-wave time difference prediction is carried out for the study horizon of l10-1 well. The logging depth is 3300 m ~ 3600 m, and the lithology is sandstone and mudstone. The porosity of the study horizon is mainly between 2% ~ 18%, and the lithology density is mainly between 2.4 g/cm and 2.7 g/cm³. Figure 2 shows the results of S-wave time difference predicted by the two models. It can be seen from the figure that the error of S-wave time difference predicted by the fitting model of measured S-wave data is large, especially in the mudstone development section, the average relative error is more than 7%, which can not meet the actual work demand. However, the characteristics of S-wave time difference predicted by Xu white model are basically consistent with those measured, and the average relative error of mudstone section is significantly reduced, The absolute error is less than 1.2%, and the average relative error is less than 3.2%, which meets the needs of practical work.

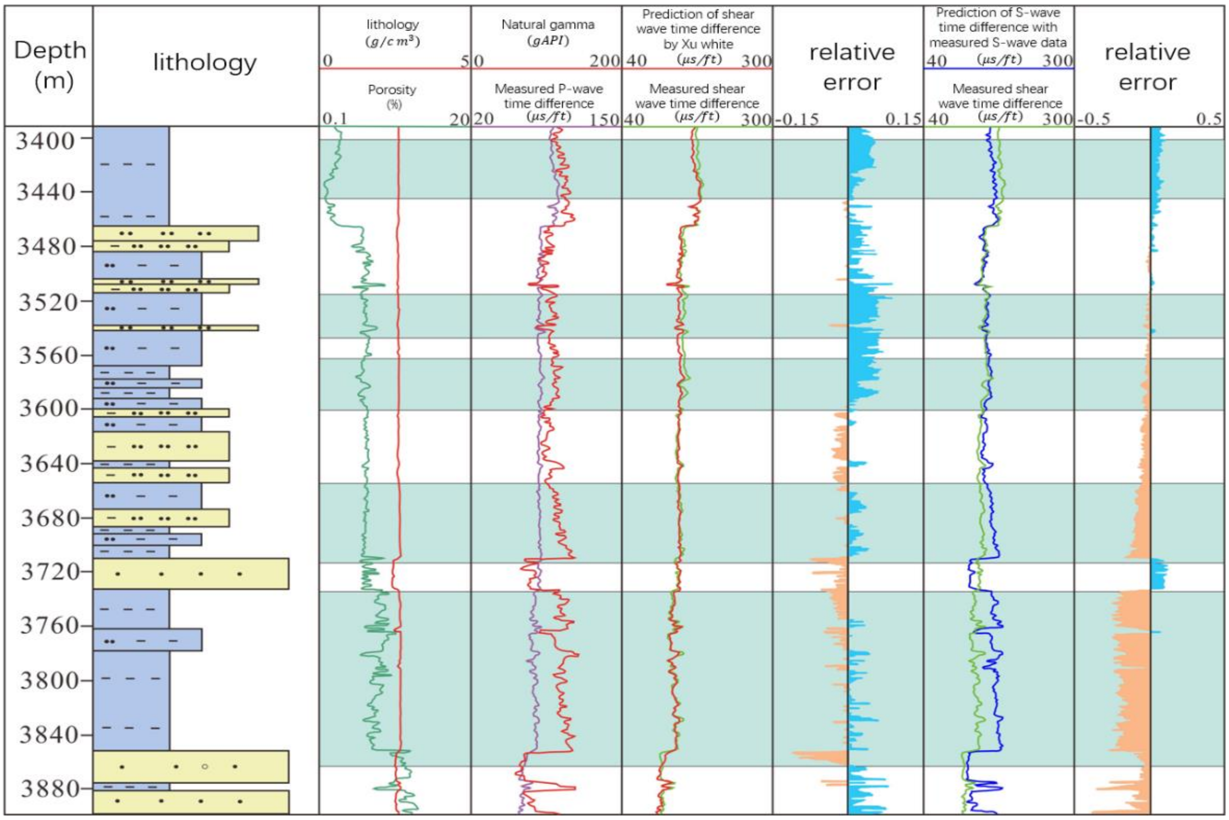

Fig. 2 Interpretation results of shear wave time difference logging in Well L10-1

5. Interpretation of dynamic rock mechanics parameters

Rock elastic parameters include young's modulus, bulk modulus, shear modulus and Poisson's ratio. Rock strength parameters mainly include compressive strength, tensile strength and shear strength [13]. Using logging data from the acoustic characteristics of rock, we can accurately obtain rock mechanical parameters, and obtain the distribution of one-dimensional mechanical parameters along the wellbore. Using the shear wave information predicted by the Xu white model established in this paper, we can calculate the dynamic rock mechanical parameters (Fig. 3) through (17) ~ (20) formula [13-15]. The results show that: the Miocene Young's modulus in the study area is between 20 GPA and 50 GPa, The Poisson's ratio is between 0.1 and 0.3, and the internal friction angle is between 20 and 40 ° The tensile strength is between 15 MPa and 30 MPa.

$$E_{\mathrm{d}} = 10^{-3}\rho V_{\mathrm{s}}^{2}\frac{3V_{\mathrm{p}}^{2}-4V_{\mathrm{s}}^{2}}{V_{\mathrm{p}}^{2}-V_{\mathrm{s}}^{2}} \tag{17}$$

$$\mu_{\mathrm{d}} = \frac{V_{\mathrm{p}}^{2}-2V_{\mathrm{s}}^{2}}{2(V_{\mathrm{p}}^{2}-V_{\mathrm{s}}^{2})} \tag{18}$$

$$S_{\mathrm{t}} = 3.75\times 10^{-4} - E_{\mathrm{d}}(1-0.78V_{\mathrm{sh}}) \tag{19}$$

$$\varphi = \frac{\pi}{12}\left[2\left(1-\frac{\mu_{\mathrm{d}}}{1-\mu_{\mathrm{d}}}\right)+1\right] \tag{20}$$

Where: E_{d} is the dynamic Young's modulus, Gpa; μ_{d} is the dynamic Poisson's ratio, dimensionless; ρ is the density of rock, $\mathrm{g/cm^3}$; V_{p} is the P-wave velocity, $\mathrm{m/s}$;V_{s} is the shear wave velocity, $\mathrm{m/s}$; V_{sh} is argillaceous content, %; S_t is the tensile strength, Mpa;φ is the internal friction angle of rock.

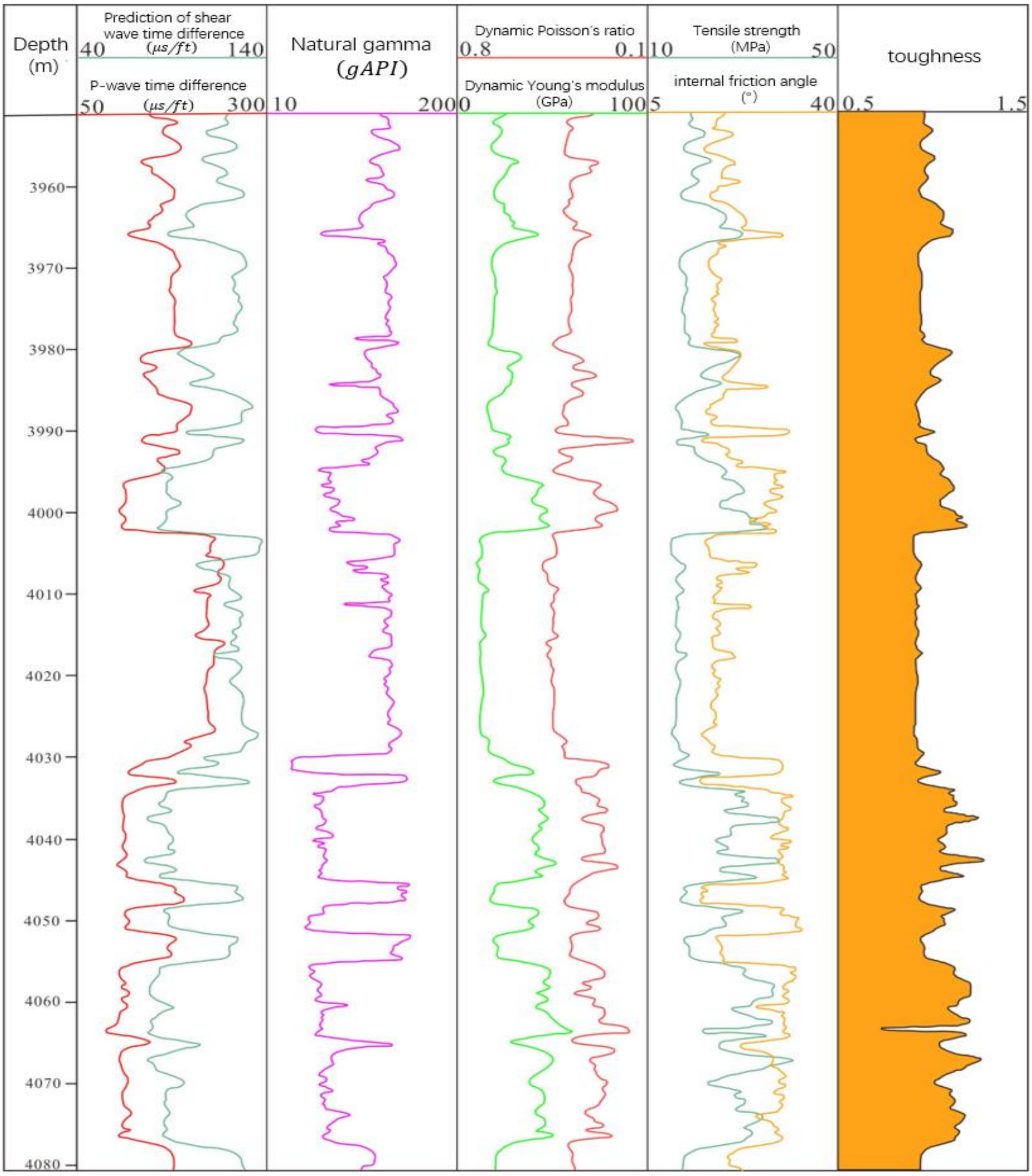

Fig. 3 Log interpretation results of rock mechanics parameters of Well L10-5

6. Conclusion

(1) Based on the measured acoustic information and other actual data, the continuous porosity curve is inversed by lithology, and the matrix bulk modulus, shear modulus, dry rock bulk modulus and dry rock shear modulus of tight sandstone in the study area are accurately characterized by the self extracting matrix modulus method and Xu white model with comprehensive consideration of pore aspect ratio, porosity and other parameters, Finally, combined with the actual situation of the work area, the white Gassmann equation is used to accurately predict the S-wave velocity of rock. The comprehensive analysis shows that the absolute error of the S-wave velocity information predicted by this method is less than 1.2%, and the average relative error is less than 3.2%, which is obviously better than the measured P-wave data fitting method, and can meet the production demand.

(2) The shear wave velocity information predicted by Xu white model is used to interpret the rock mechanics parameters of conventional logging of Miocene reservoir in Ledong district. The results show that the young's modulus is between 20-50 GPA and Poisson's ratio is between 0.1-0.3; The internal friction angle is between 20 and 40 ° The tensile strength is between 15 MPa and 30 MPa, which provides reliable rock mechanics parameters for the simulation of in-situ stress field and the optimal fracturing design of the target formation.

References

[1] Xieyuhong. The mechanism and resource prospect of high temperature and high pressure natural gas accumulation in the western South China Sea Area -- Taking Yingqiong basin as an example [j]. Oil drilling and production technology, 2016, 038 (006): 713-722

[2] Sun, Yang Changchun, Ma sanhuai, et al. Prediction method of shear wave velocity [j]. Geophysics progress, 2008 (02): 470-474

[3] Dou, Gao Gang, Liang Lin, et al. prediction of shear wave velocity based on Xu white model [j]. Petroleum geology, Xinjiang, 2016, 37 (001): 83-87

[4] Zhang Yuanzhong, zhoukaijin, zhaojianbin, et al. Study on the prediction method of shear wave logging curve of sandstone and mudstone formation [j]. Petroleum geophysical exploration, 2012 (05): 508-514.

[5] J, P, Castagna, et al. Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks[J]. Geophysics, 1985.

[6] Greenberg M L, Castagna J P. Shear-wave velocity estimation in porous rocks—theoretical formulation, preliminary verification and applications[J]. Geophysical Prospecting, 2010, 40(2):195-209.

[7] Xu Shiyong, Ma Zaitian. Fast and effective common conversion point stacking technique for converted waves [J]. Acta geophysica Sinica, 2002, 45 (004): 557-568

[8] Keys R G, Xu S. An approximation for the Xu-White velocity model[J]. Geophysics, 2002, 67(5):1406-1414.

[9] Guo Dong, Yin Xingyao, Wu Guochen. Calculation method and application of shear wave velocity [J]. Petroleum geophysical exploration, 2007, 42 (5): 535-538

[10] Wyllie M R J, Gregory A R, Gardner G H F. An experimental investigation of factors affecting elastic wave velocities in porous media[J]. Geophysics, 1958, 23(3):459-493.

[11] Kuster G T, Toksoz M N. Velocity and attenuation of seismic waves in two-phase media; Part II, Experimental results[J]. Geophysics, 1974.

[12] Gassmann F. Elastic waves through a packing of spheres[J]. Geophysics, 1951, 16(4):673-685.

[13] Lu Shikuo, Wang Di, Li Yukun, et al. Study on 3D rock mechanics parameter field of tight sandstone reservoir in Daniudi gas field, Ordos Basin [J]. Natural Gas Geoscience, 2015.

[14] Chang C, Zoback M D, Khaksar A. Empirical relations between rock strength and physical properties in sedimentary rocks[J]. Journal of Petroleum ence & Engineering, 2006, 51(3-4):223-237.

[15] Jia Lichun, Chen Yang, Yu Sheng. Wellbore stability analysis of horizontal wells based on unified strength theory [J]. Fault block oil and gas fields, 2018, 25 (05): 95-99.