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original article

Prediction of mechanical parameters for low-permeability gas reservoirs in the Tazhong Block and its applications

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Abstract:
A longitudinal distribution profile of the mechanical properties of the formations is important for the safe drilling, successful completion, and development of oil and gas reservoirs. However, the mechanical profile of the carbonate formations from the low-permeability gas reservoirs in the Tazhong (TZ) Block is hard to achieve due to the complex structural and lithological characteristics of the carbonates. In this paper, lab measurements are carried out to determine the physical and mechanical properties of the carbonate rocks of the Yingshan Formation in the TZ Block. Based on this, the relationships among density, the interval transit time and the mechanical parameters of the rocks in the TZ Block are constructed. The constructed relationships are then applied to the well-logging prediction of the mechanical profiles of the carbonate formations. The models are verified through the application to the two wells in the TZ Block, the results show that the relative errors in the predicted mechanical parameters are within 10% indicating the efficiency of the constructed models. The result of this study provides reasonable mechanical parameters for the exploration and development of the carbonate reservoirs in the TZ Block.

1. Introduction

The Tarim Basin is the third-largest oil and gas producing area in China having an estimated petroleum resources of about 24 billion tons. These oil and gas resources are mainly located in the Tabei and Tazhong (TZ) Block (Zhu et al., 2019). A well understanding of the mechanical properties of the formation rocks is critical to the processes of drilling, hydraulic fracturing, well completion, and borehole stability analysis that are essential for the exploration and development of oil and gas reservoirs (Bearman et al., 1997; Zhu et al., 2012; Hu et al., 2016; Zhang et al., 2016).

In general, the mechanical parameters of rocks can be obtained through lab measurements, well logs, and drilling information. A widely used method in evaluating the mechanical properties of rocks is deriving the mechanical properties from drilling rates according to the Mohr-Coulomb criterion (Coates and Denoo, 1981; Gommesen and Fabricius, 2001; He et al., 2020). One issue prevents the application of drilling data in analyzing the mechanical properties is that the drilling data is usually affected by many factors. It is hard to accurately evaluate the mechanical properties of formation rocks only through drilling information, for example, drilling rates. Some researchers used the strength and density of rocks to evaluate the mechanical parameters of muds and shales (Yagiz, 2001). Other researchers evaluated mechanical parameters of rocks through lab mechanical experiments. King (1983), Xie and He (2004) investigated the mechanical characteristics of rocks through the triaxial test and damage mechanics. Gstalder and Raynal (1966) investigated the mechanical parameters of rocks, such as drillability, hardness, and tensile strength through some experiment methods. Wang and Li (2007) measured the mechanical parameters of sandstones through the uniaxial compressive test, triaxial compressive test, and Brazilian split test. Although the mechanical parameters of rocks can be obtained accurately through lab measurements, these lab data are discontinuous that cannot provide a continuous description of mechanical properties for the whole formation intervals. In order to research the longitudinal distribution

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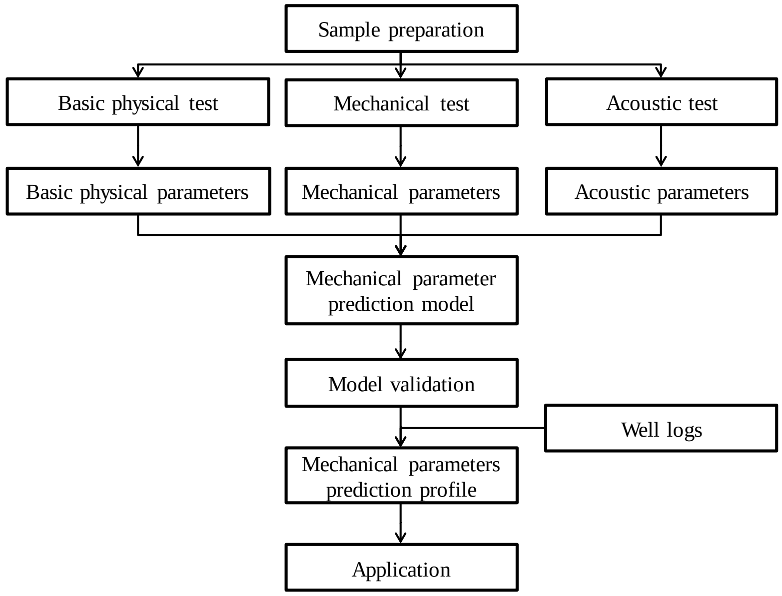

Fig. 1. Research flow chart.

characteristics of the mechanical properties of the formations, it is necessary to evaluate the mechanical characteristics of rock in combination with well logs. Well logs have been used to continuously calculate the mechanical properties of the formations providing necessary parameters for petroleum engineering (Liu et al., 2005; Ameen et al., 2009; Gui and Wan, 2012). The well logging evaluation model is usually built based on the semi-empirical relationships obtained in lab (Karakul and Ulusay, 2013; Hassanvand et al., 2018; Uyanık et al., 2019). However, the constructed methods or relationships in literatures are inapplicable to the carbonate rocks in the TZ Block due to its complex structural and lithological characteristics. Continuous and reliable mechanical profiles of the carbonate formations are still necessary for the formation evaluation and borehole stability analysis of the study area.

The purpose of this research is to build a well-logging prediction model for the mechanical properties of the Yingshan Formation carbonate rocks in the TZ Block. The physical parameters, for example, density, porosity, permeability, and acoustic velocity, and mechanical parameters, such as compressive strength, tensile strength, and elastic parameters, of the carbonate rocks were measured through lab physical and mechanical measurements. Basing on the lab data, the prediction models of the mechanical parameters of the carbonate rocks are built. Finally, the above information can be used to evaluate the pore pressure, *in-situ* stress, formation collapse pressure, and formation fracture pressure, and to conduct borehole stability analysis.

2. Experimental samples and methods

2.1 Samples

The carbonate samples are collected from the downhole in the Yingshan Formation in the TZ Block of the Tarim Basin. They will be processed into two shapes of rock samples. One is in a cylindrical shape of a diameter of 25 mm and a length of 50 mm. A total of 12 samples were prepared. They will be used in triaxial compression tests and uniaxial compression tests. The other is in disc-shape with a diameter of 25 mm and a length distribution range is 12.5 to 25 mm. 8 samples are prepared in disc shape for the Brazilian split tests. The carbonate experiment samples are dried at 60 °C for 24 hours. After drying, the rock samples are taken out to test its length, diameter, bulk density, porosity, and permeability. The instrument used for the test is HKGP-3 permeability and porosity measuring instrument. The relevant regulations of SY/T 5336-1996 “Routine Core Analysis Methods” are strictly followed at all experimental processes. The bulk density ranges from 2.68 to 2.88 g/cm^3. Porosity ranges from 1.3% to 2.7%, whereas permeability ranges from 0.0008 to 3.8423 mD.

2.2 Methods

The prediction models of the mechanical parameters of rocks can be constructed based on the physics experiments and mechanics tests of rocks. The specific method is as shown in Fig. 1.

One of the most important physical tests is ultrasonic pulse transmission measurement. The arrival time of both the P-wave and S-wave is measured under a confining pressure on 0.3 MPa. The measurement is done following the standard SY/T 6351-1998 “Laboratory Measurement of Rock Acoustic Characteristics”. Interval transit times of P-wave and S-wave is calculated based on the results of acoustic transmission tests and physics parameters of rocks.

The mechanical tests including the compression test and tensile test are conducted to obtain the mechanical parameters of rocks, after the completion of physics experiments and acoustic transmission experiments with rocks. Put the test sample into the core holder, and under certain confining pressure, continue to increase the axial stress until the rock sample ruptures. The stress-strain curve can be obtained through the triaxial compression test. The compressive strength, elastic modulus, and Poisson's ratio can be calculated through the stress-strain curve, according to the triaxial compressive test results and the Mohr-Coulomb criterion. The formula for calculating the elastic modulus (E) and Poisson's ratio (ν) is shown in Eq. (1) and Eq. (2).

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{1}$$

where E is elastic modulus in MPa; $\Delta\sigma$ is axial stress of the curve in the rock elastic deformation stage in MPa; $\Delta\varepsilon$ is strain increment of the curve in rock elastic deformation stage in %.

$$\nu = \left|\frac{\varepsilon_r}{\varepsilon_a}\right| \tag{2}$$

where ν is Poisson's ratio; ε_r is the radial strain of the curve in the rock elastic deformation stage in %; ε_a is the axial strain of curve in rock elastic deformation stage in %.

Based on the triaxial test results from different confining pressures, the stress Mohr circle can be drawn base of the test result of each sample. During the triaxial compression test, lateral pressure σ_3 (confining pressure) is applied to the rock sample, and then the axial stress is gradually increased until the rock ruptures to obtain the large principal stress σ_1 at the time of rupture. Based on this result, a stress Mohr's circle can be obtained. Change the lateral pressure (confining pressure) to σ_3', and apply axial pressure until the rock breaks, to obtain another large principal stress σ_1' at the time of rupture, and to obtain another stress Mohr's circle. The envelope of the stress circle is drawn, after the Mohr's circle combination of 2∼3 samples is drawn. The envelope is on the vertical axis the intercept and slope of the line is the cohesion (C) and friction angle (φ) of the rock. The method is as follows Fig. 2.

The tensile test is conducted by the Brazilian split method. Place the rock sample on the test platform, when the concentrated load is applied along the diameter of the disc-shaped rock sample, the rock sample will split along the diameter direction of the force after being stressed. The tensile strength of the rock can be obtained by calculation, based on the maximum load value obtained from the test. The relevant provisions of SY/T 5336-1996 "Routine Core Analysis Methods" and GB/T 50266-99 "Engineering Rock Mass Test Method Standard" are strictly followed at all experiments processes. The formula for calculating tensile strength (σ_t) the is shown in Eq. (3).

$$\sigma_t = \frac{2P_{\max}}{\pi d t} \tag{3}$$

where σ_t is tensile strength in MPa; $P_{\max}$ is the maximum load when the rock specimen fails in N; d is the diameter of the rock in m; t is the thickness of the rock in m.

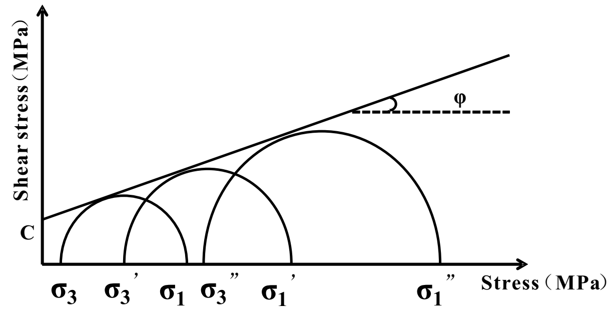

Fig. 2. Stress circles around rock failure of the triaxial compression test.

After obtaining all experimental test results, the correlation will be analyzed between the mechanical parameters and physical parameters of rocks, such as interval transit time of P-wave and S-wave, density, and other parameters, and the models of the relationship will be established between the mechanical parameters and foundation parameters. This relationship is the prediction models of the mechanical parameters of rocks. The logging prediction profile of the mechanical parameter of rocks can be obtained, and the longitudinal distribution characteristics of whole well formation can be analyzed, based on the established model and combined with the well logs.

2.3 Results and Discussion

2.3.1 Acoustic test results

The acoustic test results are shown in Fig. 3. The interval transit time of P-wave ranges from 46.01 to 61.75 μs/ft, and the interval transit time of S-wave ranges from 74.06 to 130.02 μs/ft.

2.3.2 Mechanical test results

Mechanical test results of rocks are shown in Fig. 4. It can be seen from Fig. 4 that the uniaxial compressive strength (UCS) of the rock ranges from 133.28 to 236.83 MPa; the tensile strength (σ_t) ranges from 3.45 to 6.29 MPa; the elastic modulus (E) ranges from 20.44 to 34.90 GPa; the Poisson's ratio (ν) ranges from 0.16 to 0.33; the cohesion (C) ranges from 10.03 to 34.77 MPa; the internal friction angle (φ) ranges from 11.97° to 35.54°. The strong heterogeneity of the rocks in the study block results of the discrete distribution of the strength and elastic parameters of the rocks.

2.3.3 The acoustic response to the mechanical parameters of rocks

The mechanical test of rocks can only obtain the strength characteristics at a single point, and the longitudinal distribution characteristics of mechanical properties in the carbonate formations cannot be obtained. Based on the experimental results of rocks, the basic physical parameters, such as rock density and interval transit time of P-wave, are used as independent variables. The mechanical parameters of rocks are used as the dependent variable. The logging prediction models of the mechanical parameters are established by regression

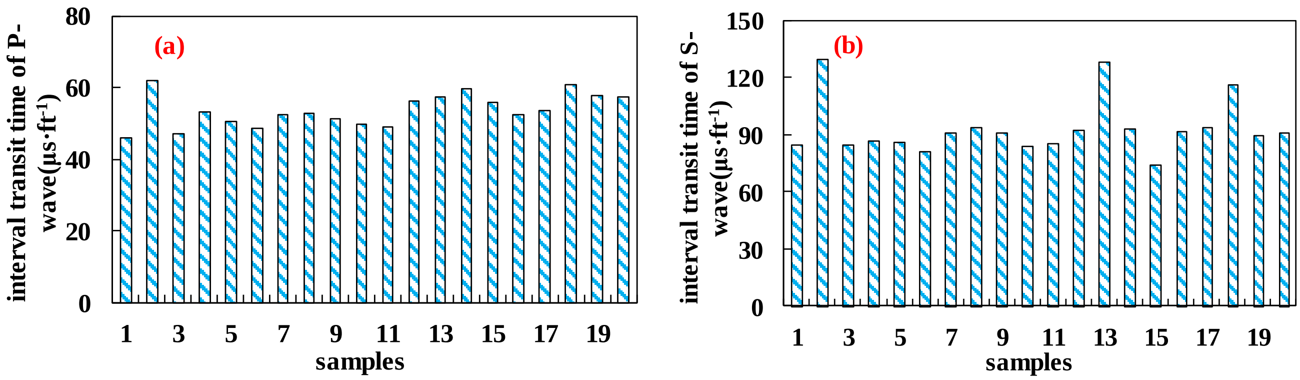

Fig. 3. The tests results of acoustic. (a) interval transit time for P-wave; (b) interval transit time for S-wave.

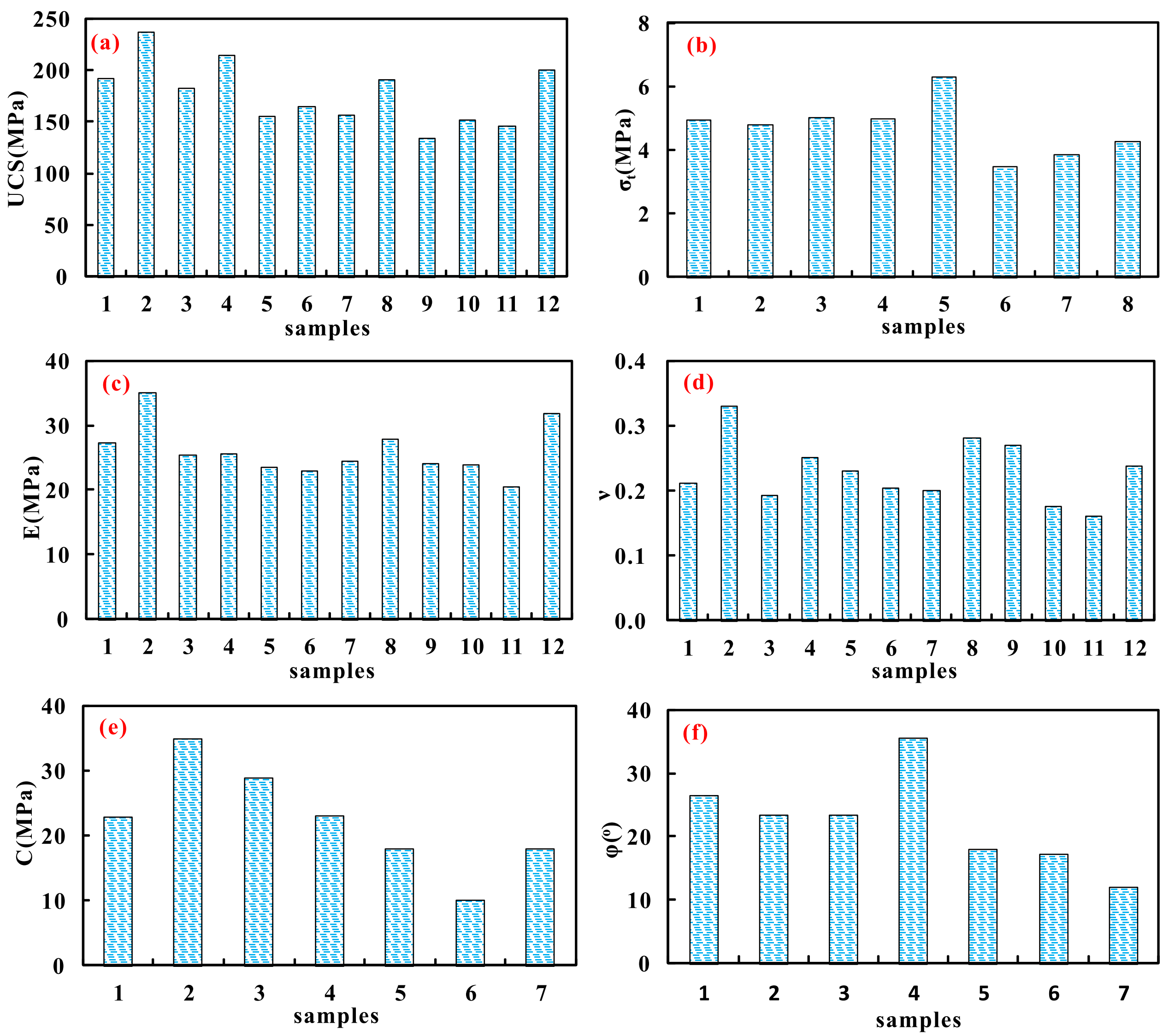

Fig. 4. The tests results of the mechanical parameters. (a) uniaxial compressive strength (UCS); (b) tensile strength (σ_t); (c) elastic modulus (E); (d) Poisson's ratio (ν); (e) cohesion (C); (f) friction angle (φ).

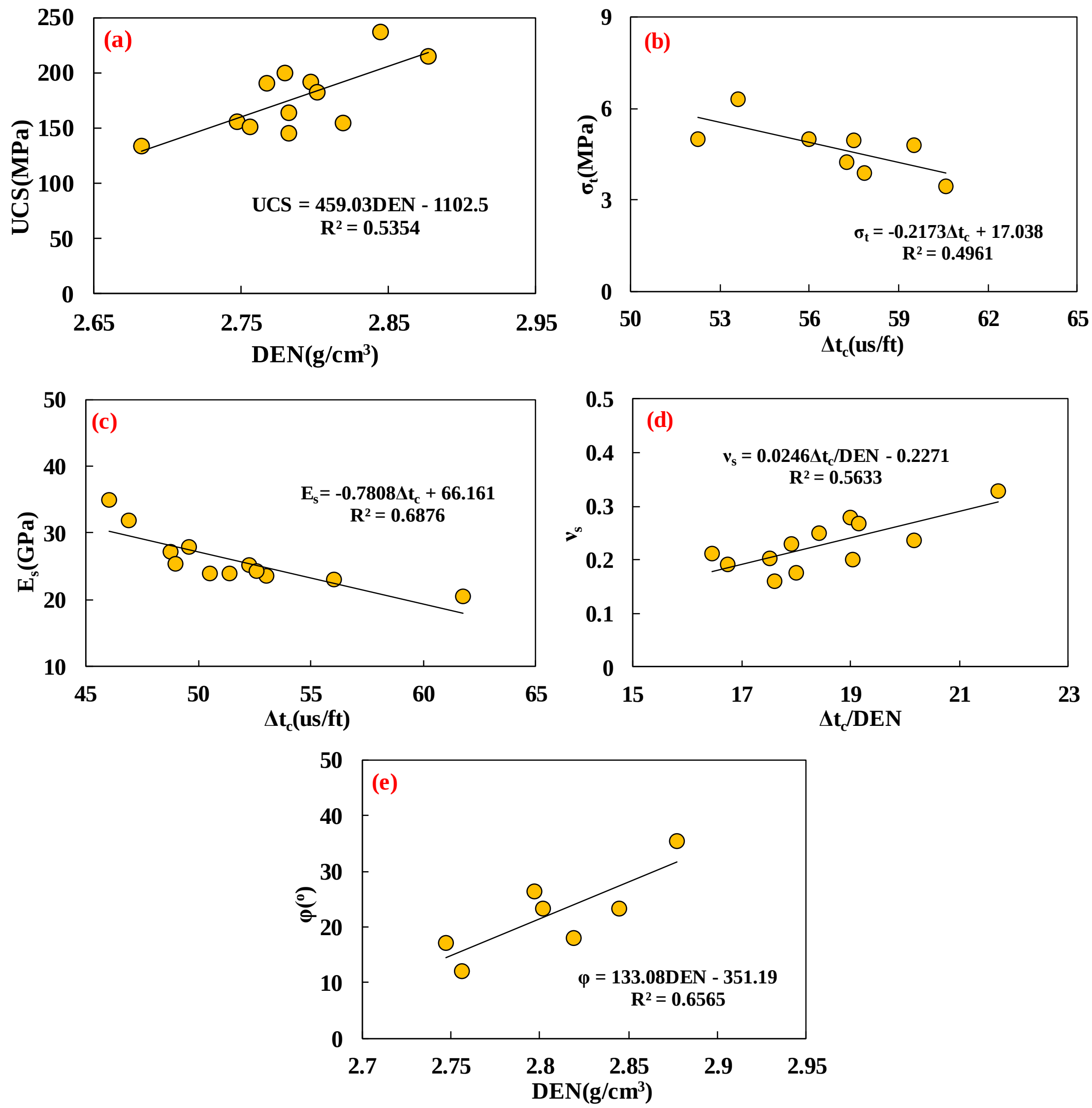

Fig. 5. The calculation models of the mechanical parameters. (a) the relationship between UCS and DEN; (b) the relationship between σ_t and Δt_c; (c) the relationship between E_s and Δt_c; (d) the relationship between v_s and $\Delta t_c/DEN$; (e) the relationship between φ and DEN.

fitting by the least square method. The mechanical parameter profile can be further obtained based on the established model and well logs. Analysis and comparison results show. Logging prediction models with good correlation and conformity to the reality are finally selected, and the accuracy of the models is verified. The logging prediction models are shown in Table 1, Δt_c is interval transit time of P-wave in laboratory in μs/ft; DEN is bulk density in g/cm^3, subscript s means static; φ is internal friction angle in $^\circ$. And the corresponding relationships are shown in Fig. 5.

In order to verify the reliability of the established logging prediction models of the mechanical parameters of carbonate rocks. It is necessary to test the accuracy of all models. Correct core depth before the model check to match the core depth with the logging depth. The model checking method is to compare the discrete data obtained through laboratory testing and not used for the model establishment with the mechanical parameters obtained through the prediction models (as shown in Fig. 6 and Fig. 7), and analyze the relative error between the measured data and the predicted data. If the relative errors are within 10%, it shows that the established logging prediction models are reliable. The error between the mechanical parameters was measured and the mechanical parameters by predicting are show in Table 2. It can find from the analysis of the data in Table 2 that the errors of the majority of the measured and predicted mechanical parameters of rocks are within 10%, indicating that the established models are reliable.

3. Application

The logging prediction profile of rock mechanical parameters can be established through the above logging prediction models combined with well logs, and pore pressure, *in-situ* stress, collapse, rupture pressure, and safe drilling fluid density window can be derived based on related theories to carry

Table 1. The logging prediction models of the mechanical parameters of rocks.

Paramerer	Unit	Calculation models	Correlation coefficient	Numbering
σ_c	MPa	σ_c=459.03×DEN−1102.5	R^2=0.5354	(4)
σ_t	MPa	σ_t=-0.2173×Δt_c+17.038	R^2=0.4961	(5)
E_s	GPa	E_s=-0.7808×Δt_c+66.161	R^2=0.6876	(6)
v_s	Dimensionless	$v_s=0.0246\times\frac{\Delta t_c}{DEN}-0.2271$	R^2=0.5633	(7)
φ	°	φ=133.08×DEN−351.19	R^2=0.6565	(8)

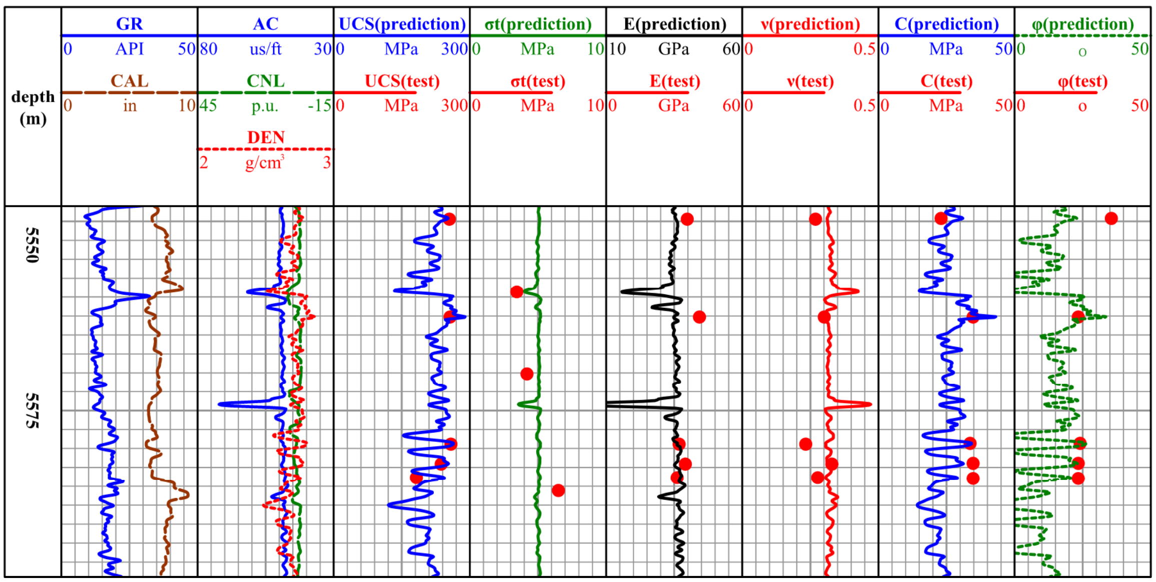

Fig. 6. Verification the accuracy of models in Well X.

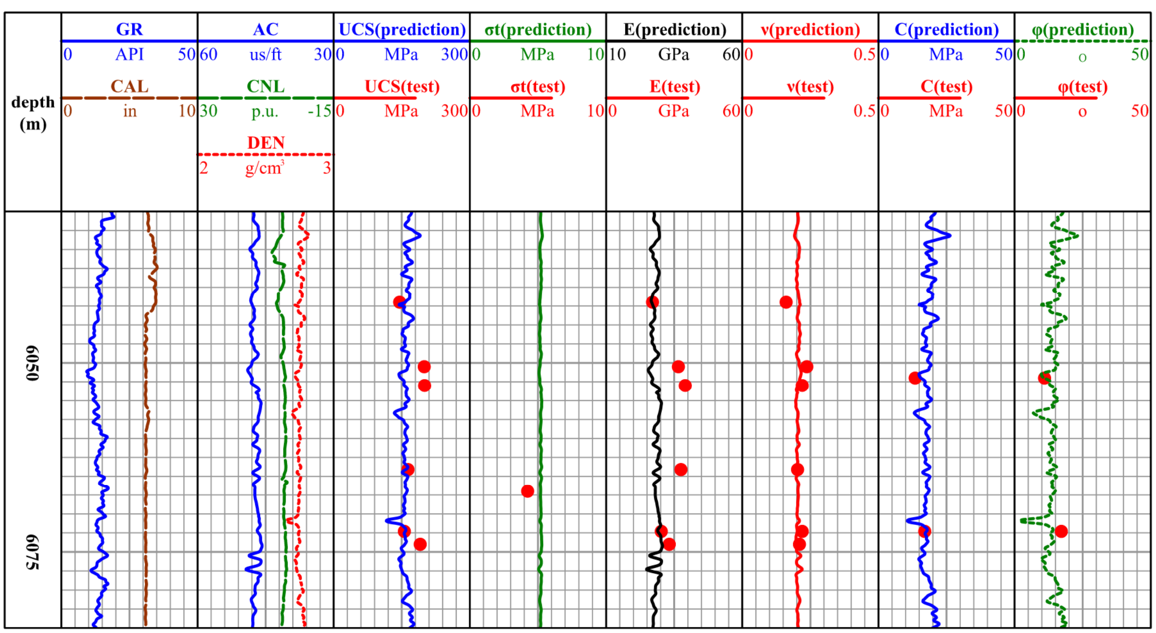

Fig. 7. Verification the accuracy of models in Well Y.

Table 2. The logging prediction models of the mechanical parameters of rocks.

Well name \ Relative error (%)	σ_c	σ_t	E	ν	C	φ
X	9.41	12.49	10.78	5.65	8.92	8.72
Y	7.64	11.18	11.76	6.75	7.26	9.57

out borehole stabilization evaluation. During the establishment of the logging prediction profile, the accuracy of pore pressure has a great impact on subsequent calculation results. Therefore, taking Well Z as an example, the equivalent depth method and effective stress method are used to predict the pore pressure. Compared with the measured pressure, it is found that the pore pressure calculated using effective stress is the closest to the measured point. The main reason for the analysis is that the longitudinal distribution of pure mudstone is difficult to be found in carbonate formations, which caused great difficulties in the establishment of compaction curves. This method is not suitable for carbonate reservoirs. Therefore, the effective stress method is used to predict the pore pressure of the formation in the study block (Zhang, 2011). According to the effective stress theorem, the pore pressure can be obtained by knowing the overburden pressure and effective stress. The overburden pressure is obtained from the density well logs. Therefore, the pore pressure can be calculated as long as the effective stress is obtained (Reyes and Osisanya, 2000). Existing studies shown that the speed of acoustic propagation is more sensitive to changes of effective stress (Siggins and Dewhurst, 2003). Researchers at home and abroad established a series of quantitative relationships between the speed of acoustic propagation and effective stress through experimental research and theoretical analysis (Khaksar and Griffiths, 1999). The acoustic value will be affected by many factors for complex formations. Predict effective stress based on sonic well logs alone will cause large errors. Based on the analysis of the response characteristics of the physical quantity of the pore pressure logging curve, a multiple nonlinear regression analysis is performed on the pore pressure test data and the logging curve. The effective stress can be calculated. The pore pressure of the formation can be calculated by using Eq. (9), based on the overburden pressure calculated from the density well logs and the effective stress.

$$P_p = \sigma_v - \frac{d_g}{1.068} + 2.1641\ln(1.02468GR) - 7.7239e^{-0.005495AC} - 3.71098e^{0.40845DEN} \tag{9}$$

where P_p is pore pressure in MPa; σ_v is vertical principal stress in MPa; d_g is depth gradient in depth/100; GR is natural gamma in API; AC is the transit time of P-wave in μs/ft.

In order to verify the accuracy of the model, the comparison is made between the predicted values and measured values of the pore pressure of 6 wells in this block. The relative errors between the predicted values and the measured pressure values of the model were mostly less than 10%, which meets the engineering requirements.

Based on the established prediction models of the mechanical parameters and the pore pressure model, the logging prediction of *in-situ* stress can be performed (Aadnoy, 1990). Among them, the combined spring relationship model (Eq. (10)) (Meng et al., 2011) comprehensively considers the effects of stratum rock mechanical properties, pore pressure, and tectonic effects on *in-situ* stress, and has been widely used in recent years. The calculation of each principal stress component is shown in Eq. (10) and Eq. (11).

$$\begin{cases} \sigma_H = \dfrac{\nu}{1-\nu}\sigma_v + \dfrac{1-2\nu}{1-\nu}\alpha P_p + \dfrac{E}{1-\nu^2}\varepsilon_H + \dfrac{\nu E}{1-\nu^2}\varepsilon_h \\ \sigma_h = \dfrac{\nu}{1-\nu}\sigma_v + \dfrac{1-2\nu}{1-\nu}\alpha P_p + \dfrac{E}{1-\nu^2}\varepsilon_h + \dfrac{\nu E}{1-\nu^2}\varepsilon_H \end{cases} \tag{10}$$

$$\sigma_v = \int_{H_0}^{0}\rho_0(h)gdh + \int_{H}^{H_0}\rho(h)gdh \tag{11}$$

where σ_H is maximum horizontal principal stress in MPa; σ_h is minimum horizontal principal stress in MPa; α is Biot's coefficient, which can be taken as 0.9; ε_H and ε_h represent the strain coefficient along the direction of the maximum principal stress and the direction of the minimum principal stress and the direction of the minimum principal stress, ε_H and ε_h of the study area is 1.527×10^{-3} and 1.826×10^{-4}, respectively; H_0 is the depth of well log starting point in m; $\rho_0(h)$ is the density of the unlogged section at the depth point h in g/cm^3; $\rho(h)$ is well log density at depth point h in g/cm^3; g is the acceleration of gravity in kg·m/s^2, preferably 9.8.

The calculation of formation collapse pressure is based on the Mohr-Coulomb criterion (Liu, 2004; Liu et al., 2004; Al-Ajmi and Zimmerman, 2016). The calculation model is shown in Eq. (12).

$$\rho_{mc} = \frac{\eta(3\sigma_H - \sigma_h) - 2CK + \alpha P_p(K^2-1)}{gh(K^2+\eta)} \times a \tag{12}$$

$$K = \tan^{-1}(\frac{\pi}{4} - \frac{\varphi}{2}) \tag{13}$$

where ρ_{mc} is the equivalent density of formation collapse pressure in g/cm^3; η is non-linear correction coefficient; h is the depth in m; a is the unit conversion factor, equaling 10^3 here.

The fracture pressure of the formation mainly depends on the tensile strength of the formation and the state of the *in-situ* stress. Under the conditions of knew *in-situ* stress and rock strength of the formation, the fracture pressure of the formation is shown in Eq. (14).

$$\rho_{mf} = \frac{3\sigma_H - \sigma_h - \alpha P_p + \sigma_t}{gh} \times a \tag{14}$$

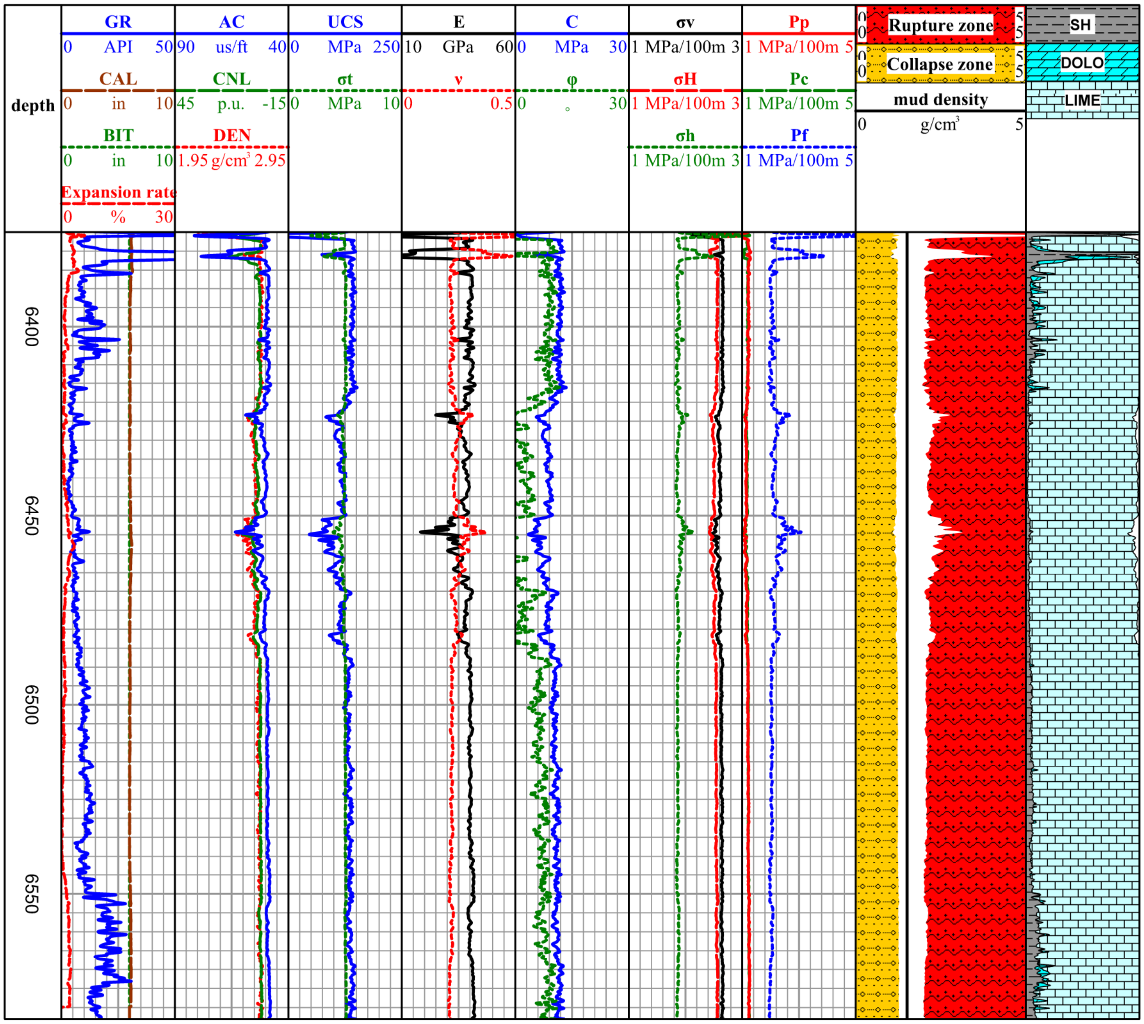

Fig. 8. Prediced profile of the mechanical parameters in Well Z.

where ρ_{mf} is the equivalent density of formation fracture pressure in g/cm^3.

Finally, the wellbore stability is analyzed, based on the mechanical parameters of rocks, pore pressure, *in-situ* stress, and collapse and rupture pressure.

The logging prediction profile of mechanics parameter of Well Z is shown in Fig. 8, and it can be seen from Fig. 8 that the pore pressure P_p of the well ranges from 65.77 to 83.27 MPa; the vertical principal stress ranges from 157.96 to 175.80 MPa; the horizontal maximum principal stress ranges from 156.28 to 169.20 MPa; the horizontal minimum principal stress ranges from 116.68 to 138.42 MPa; collapse pressure ranges from 68.76 to 82.54 MPa; fracture pressure ranges from 122.99 to 198.36 MPa. The security window of drilling fluid density was obtained through the model, and it ranges from 1.19 to 2.03 g/cm^3, and the drilling fluid density used in the actual drilling process of this well is 1.51 g/cm^3. According to the analysis of the well logs, it can be seen that the borehole diameter is approximately equal to the size of the drill bit, and no expansion or contraction occurs, and the density of the drilling fluid used is within the security window of drilling fluid density. It can be seen the prediction models of the mechanical parameter can be effectively applied in this block.

4. Conclusions

1) The mechanical properties of the carbonates in the TZ Block are determined having its uniaxial compressive strength ranging from 133.28 to 236.83 MPa, the tensile strength ranging from 3.45 to 6.29 MPa, the elastic modulus ranging from 20.44 to 34.90 GPa, the Poisson's ratio ranging from 0.16 to 0.33, the cohesive force ranging from 10.03 to 34.77 MPa, and the internal friction angle ranging from 11.97° to 35.54°. The mechanical properties of the carbonates, even for those collected in the sample formation, in the TZ Block are significantly different indicating that the carbonate rocks are strongly heterogeneous.
2) The investigation results illustrate that the rock mechanical properties correlate closely with the interval transit time of wave and density. The Poisson's ratio of the carbonates rock is sensitive to the interval transit time of wave and density. The tensile strength and elastic modulus are sensitive to the interval transit time of wave.

The uniaxial compressive strength and internal friction angle are sensitive to density. The calculation models of rock mechanical parameters can be established and applied based on the interval transit time of wave and density to avoid errors caused by using other empirical models.

3) The prediction models of rock mechanics mechanical parameters can be effectively used to are effective in evaluating the longitudinal distributions of the mechanical properties, pore pressure and *in-situ* stress and analyzing the wellbore stability of the longitudinal distribution of carbonate rocks formations in the TZ Block, as well as the pore pressure and *in-situ* stress, and carry out wellbore stability analysis.

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Conflict of interest

The authors declare no competing interest.

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