Drillability characteristics of formation and evaluation of bit selection for the Zhongtaishan structural strata in Sichuan Basin, China

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Abstract: Selecting a suitable bit for a specific formation is very important in increasing the rate of penetration (ROP) and reducing the drilling cost during the drilling process. Drillability and rock mechanical parameters are frequently used to evaluate the resistance of strata to drilling engineering. Based on the drilling well history data for the Zhongtaishan structural strata in the Sichuan Basin, it can be observed that the slow ROP and high drilling cost have become critical factors in restricting the efficient development of tight gas in this tectonic region. Furthermore, a new model for the rock drillability index was established based on the experimental rock drillability data under simulated bottom-hole conditions. Part of the drillability test data was used to verify the accuracy of the model, which can accurately describe the effect of wellbore pressure on drillability. Well history and logging data were also used to calculate the rock mechanics parameters and rock drillability index. In the Xujiahe Formation, characterized by high uniaxial compressive strength (UCS) and drillability index, the Poisson's ratio of the formation rock was approximately 0.21–0.24, the elastic modulus was 80 GPa–110 GPa, the average value of the internal friction angle increased from 40° to 45°, and cohesive increased from 18 MPa to 36 MPa. The formation drillability index without wellbore pressure ranged from 5–7, whereas that under wellbore pressure conditions ranged from 8–9 with a high Cerchar abrasion index (CAI). Mechanical specific energy (MSE) models were used to optimize the bit quantitatively, and the results demonstrated that the SH633, HJ537GK, I437, and KPMD1642DRT combined drill bits were more suitable for the Da’anzhai, Zhenzhuchong member of Ziliujing Formation, and the 6th, 3rd, and 2nd variables of the Xujiahe Formation respectively.
Keywords: Logging data; Rock mechanics characteristics; Bit selection; Drillability

1 Introduction
The formation of Zhongtaishan structurals in the Sichuan Basin consists of an upper Triassic Xujiahe Formation (true vertical depth (TVD), 3940–3295 m), Lower Jurassic Ziliujing (TVD, 3295–2985 m), middle formation Lianggaoshan (TVD, 2985–2895 m), Shaximiao (TVD, 289–1340 m), and upper formation Suining (TVD, 1340–800 m). It is a medium-hard to hard formation, which is primarily fine sandstone with mudstone and has high rock strength, poor formation drillability, and complex formation. This restricts the exploration and development of a reservoir in the Zhongtaishan area [1]. Many studies have been conducted on the rock characteristics and individualization of drill bits in different drilling formations. For example, Mason [2] reported that the formation hardness and compressive strength correlated with shear travel time, which led to the development of bit selection. This method was used in the best roller-cone bit selection for Blocker field in East Texas, USA. Rock hardness, drillability, shear strength, and plastic factor calculated using logging data were the input parameters of the gray clustering function built for the bit selection. Meanwhile, the Teale mechanical specific energy (MSE) model is a conventional method for breaking rocks [3]. The drilling pressure and torque as floor parameters cannot be incorporated into the model without adjusting the downhole values during the drilling process. Bit efficiency evaluation while drilling based on the Teale MSE model was applied in the analysis of the Daqing Field located in China [4].

Bit selection belongs to the rock characteristics of drilled formation and performance of the drill bit. Although there are appropriate matching bits, all formations reduce downhole accidents, improve the rate of penetration (ROP), and achieve fast and economical drilling goals. In the current study, the rock mechanics and drillability profiles were established by using the acoustic logging data of one well in Zhongtaishan structural. Then, the MSE model was employed to evaluate the bit performance for bit selection. Further, we reported the appropriate bits that helped improve ROP.

2 Methods
The shear travel time responds well to the mechanics properties of rocks [5]. The Poisson's ratio (\( \mu_d \)), elastic modulus (\( E \)), internal friction angle (\( \varphi \)), cohesion (\( C_0 \)), uniaxial compressive strength (UCS) and rock drillability index (\( K_d \)) were calculated by using Equations (1) to (8), along with acoustic logging data:

\[
\mu_d = \frac{(V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)},
\]

\[
E = 2.8156 \left[ \frac{DEN \cdot V_s^2 (3V_p^2 - 4V_s^2) \cdot 10^{-3}}{V_p^2 - V_s^2} \right]^{0.8634},
\]

\[
\varphi = \frac{\pi}{12} \left[ 2(1 - \mu_d) + 1 \right],
\]
$C_o = 5.45 \times 10^{-15} (1 - 2 \mu_d) \left( \frac{1 + \mu_d}{1 - \mu_d} \right)^2 \cdot D_{EN}^2 \cdot V_p^4 \left( 1 + 0.78 V_{cl} \right), \quad (4)$

where $D_{EN}$ is the rock density, g/cm$^3$, and $V_{cl}$ is clay content, %. Here, $V_{cl}$ could be calculated as

$$V_{cl} = \frac{2^G \Delta G - 1}{2^G - 1}, \quad (5)$$

where $G$ is the experimental coefficient, and $\Delta G$ is correction factor for natural gamma rays, which can be calculated as

$$\Delta G = \frac{GR - \text{min}(GR)}{\text{max}(GR) - \text{min}(GR)}. \quad (6)$$

UCS can be determined by acoustic time [6], which is expressed as

$$UCS = 0.77 \cdot \left( \frac{304.8}{AC} \right)^{2.98}. \quad (7)$$

Rock drillability has the empirical relationship with acoustic time [7] expressed as

$$K_d = 12.162 \cdot e^{-0.036 \frac{AC}{0.3048}}. \quad (8)$$

The rock drillability test under simulated bottom-hole conditions shows that the borehole pressure of the formation pressure is an important factor, which affects the rock drillability. According to the test results under borehole pressure [1], the rock drillability relationship under the pressure can be established as follows:

$$K_{cd} = K_d + b (P_d - \alpha P_p) \cdot e^{-\nu (P_d - \alpha P_p)}. \quad (9)$$

The abrasive coefficient has a good correlation with the acoustic characteristics and the rock mechanics parameters. The international rock mechanics association (IRMA) has adopted the abrasive test method and the Cerchar abrasion index (CAI) as the recommended methods of rock mechanics. These are also widely used for rock abrasive evaluation in mining, construction, drilling, and other engineering fields. The CAI, which has good correlation with rock mechanics parameters and acoustic characteristics, can be calculated as follows [8]:

$$CAI = -0.05 + 0.03 \cdot UCS - 8 \times 10^{-4} \times V_p + 0.08E. \quad (10)$$

The MSE method is used to identify the efficiency of actual drilling. This method, which is proposed based on the effectiveness of the input energy on rock damage, mainly focuses on two aspects of rock-breaking process factors: formation factor and input energy factor, which are effective reflections for analyzing whether the drill bit fits the formation [9]. In 1965, in order to conduct numerous experiments on various types of rocks with different drills, Teale proposed the theory of MSE, which refers to the energy required to break a unit volume of rock [3]. MSE is expressed as
\[ M = \frac{4W}{\pi D_b^2} + \frac{480rT_b}{D_b^2 ROP}. \] (11)

As there is no drilling torque, the Pessier model [10] is adopted:

\[ T_b = \frac{\mu WD_b}{36}. \] (12)

3 Results
The mechanical characteristics of formation rocks were calculated using the logging data of a well in the Zhongtaishan structural. The results of the Poisson's ratio and elastic modulus are shown in Figure 1. As can be seen, the elastic modulus of the Suining Formation in the Jurassic upper member was approximately 55 GPa, and the Poisson's ratio was approximately 0.245. The elastic modulus of the Shaximiao Formation in the middle Jurassic member, Lianggaoshan Formation, and lower Jurassic Ziliujing Formation decreased from 60 GPa to 45 GPa, before gradually increasing to 60 GPa with an increase in the depth of the strata. As can be seen, the fluctuation was large, whereas the Poisson's ratio showed a decreasing trend. Further, the elastic modulus of the upper Triassic Xujiahe Formation showed an increasing trend along with increasing depth of approximately 90 GPa. The Poisson's ratio fluctuated between 0.236–0.240.

As shown in Figure 2, the trend of the curve of the internal friction angle and cohesion of rocks was stable. In the shallow formation, namely, the Suining Formation of the upper Jurassic and Shaximiao Formation of the middle Jurassic, the values of internal friction angle and cohesion of rock showed variations with the internal friction angles and cohesion values fluctuating between 40° and 44° and between 12 and 22 MPa, respectively. In the Lianggaoshan Formation, the two variables increased rapidly to 48° and 43 MPa, before decreasing to 44° and 22 MPa, respectively, in the lower Jurassic Ziliujing Formation. In the Xujiahe Formation of the upper Triassic, the 6th, 4th, and 3rd variables of the Xujiahe Formation of the angle of internal friction and cohesion of rock showed stability. However, the value was higher, and the angle of internal friction was 47°, whereas the cohesion value was 35 MPa on average. In addition, the 5th and 2nd variable Xujiahe Formation can be classified as sandstone formation. On average, the two aforementioned variable values were smaller at 44° and 22 MPa, respectively.

As shown in Figure 3, the two strata remain constant in the Suining Formation of the upper Jurassic; moreover, the CAI and UCS of the rocks were stable at 3 and 90 MPa, respectively. The UCS of the rocks in the Shaximiao Formation of the middle Jurassic first decreased to 70 MPa and then gradually increased to 100 MPa. The UCS increased sharply to 160 MPa in the Lianggaoshan Formation, and then decreased to approximately 90 MPa in the Ziliujing Formation of the lower Jurassic, thereby exhibiting high fluctuation. The abrasibility of the three strata showed the same trend. In the middle Jurassic Shaximiao Formation, it was stable between 1 and 3, showed high fluctuation and then increased sharply. In the Xujiahe Formation of the upper Triassic, the CAI reached 7, and the UCS of the rocks increased to 180 MPa. The characteristics of the formation rock strength in the aforementioned well variable, the UCS and CAI of the rock at the well depth at <2600 m, showed minor changes. In comparison, the UCS and CAI of the rock in the well variables between 2800 and 3000 m and that <3400 m increased rapidly with high fluctuations.
As shown in Figure 4, the trends of formation drillability and rock drillability curves are constant. The formation drillability of the horizontal axis is two levels higher than that of the drillability, indicating that the drillability under borehole pressure is greater than that without such a pressure. The drillability of the Suining Formation in the upper Jurassic was approximately 7, and this subsequently increased to 7.5 when the depth was raised. In comparison, the formation drillability in the Suining Formation of the upper Jurassic, the Shaximiao Formation of the middle Jurassic variable, and the Lianggaoshan and Ziliujing Formation of the lower Jurassic decreased with an increase in depth, reaching a minimum of approximately 7 at 1500 m, after which it increased continuously. The maximum value was 9 at a range of 2800–3000 m. In the Xujiahe Formation of the upper Triassic, the drillability of the formation, which belonged to the hard formation, was stable at approximately 8.5.

![Figure 1. Results of the elastic modulus and Poisson's ratio](image1)

![Figure 2. Results of the internal friction angle and cohesion](image2)
4 Drill bit performance evaluation and analysis

The data obtained upon calculating the MSE and Pessier model are listed in Table 1.

| SN | \(D_b\) (mm) | \(W\) (kN) | \(\mu\) (rpm) | \(ROP\) (m/h) | \(T_b\) (kN \cdot m) | \(M\) (MPa) | Stratum | Type | Manufacturer | Model |
|----|---------------|-------------|---------------|--------------|----------------|------------|---------|------|-------------|-------|
| 1  | 311.2         | 160         | 0.65          | 16           | 1.86           | 0.90       | Da’anzhai | PDC  | Chuanshi    | SH633 |
| 2  | 311.2         | 124         | 0.68          | 68           | 4.87           | 0.73       | Da’anzhai | PDC  | HLF         | HS5164SBU |
| 3  | 311.2         | 123         | 0.88          | 25           | 2.69           | 0.94       | Zhenzhuchong | PDC  | Chuanshi    | SH633 |
| 4  | 311.2         | 144         | 0.85          | 64           | 3.35           | 1.06       | Zhenzhuchong | PDC  | HLF         | HS5164SUMK |
| 5  | 311.2         | 117         | 0.85          | 66           | 1.68           | 0.86       | Zhenzhuchong | PDC  | HLF         | HS5164SBU |
| 6  | 311.2         | 146         | 0.65          | 34           | 2.16           | 0.82       | Zhenzhuchong | Cone | Kingdream   | HJ537GK |
| 7  | 311.2         | 88          | 0.83          | 41           | 0.55           | 0.63       | Zhenzhuchong | PDC  | Great       | GS1635R |
| 8  | 311.2         | 93          | 0.68          | 35           | 1.00           | 0.55       | Xu6      | Cone | TORO        | RZ0475 |
| 9  | 215.9         | 138         | 0.65          | 36           | 1.23           | 0.54       | Xu6      | Cone | Kingdream   | HJT537GK |
| 10 | 215.9         | 131         | 0.75          | 38           | 2.87           | 0.59       | Xu3      | PDC  | Chuanshi    | SH522 |
| 11 | 215.9         | 100         | 0.77          | 28           | 2.30           | 0.46       | Xu3      | CD   | Kingdream   | KPMID1642DRT |
| 12 | 215.9         | 115         | 0.8           | 30           | 2.65           | 0.55       | Xu2      | CD   | Kingdream   | KPMID1642DRT |
| 13 | 215.9         | 107         | 0.81          | 31           | 2.75           | 0.52       | Xu2      | CD   | Kingdream   | KPMID1642DRT |
| 14 | 215.9         | 132         | 0.85          | 38           | 3.08           | 0.67       | Xu2      | PDC  | Chuanshi    | SH522 |

The 6th, 3rd, and 2nd variables of the Xujiahe Formation are referred to as Xu6, Xu3, and Xu2,
respectively. In addition to the cone bits, the combined drill bits and impregnated diamond bits are referred to as Cone, CD, and ID, respectively, in Table 1.

Figure 5. Results of the MSE of the x-1 well section

As indicated in Table 1, a comparative evaluation of the effect of the drill bits of five formations (i.e., the Da’anzhai and Zhenzhuchong variables as well as the 6th, 3rd, and 2nd variables of the Xujiahe Formation) showed that the selection of different drill types had significant effects on the drilling speed of the drilled formations. The effects of the Zhenzhuchong variable and 6th Xujiahe Formation drills were significantly lower than those of the other variables.

The Da’anzhai variable of the Ziliujing Formation is located at 298–3050 m. It is mainly composed of black, yellow-green, and non-thick interbedded limestone, with purplish-red mudstone in the upper part as well as marl and limestone fine conglomerate convex mirror body. The average drillability level is 9, and the UCS of the rock is 180 MPa. A comparison between the two PDC drill bits of the Chuanshi SH633 and HLF HS5164SUMK revealed that the difference in MSE was approximately 28.79%. The ROP of the HS5164SUMK can reach 4.87 m/h, whereas the ROP of SH633 was 1.86 m/h. However, the revolutions per minute (RPM) of the HS5164SUMK was 68 r/min, which was approximately 4.3 times the mechanical speed of the SH633. Therefore, by analyzing MSE, we can see that it would be more appropriate to use SH633 PDC in this formation.

The Zhenzhuchong variable of the Ziliujing Formation is 3090–3260 m and is mainly composed of fuchsia shale. The average drillability grade is 8.1, and the UCS of the rock is 100 MPa, which is a hard texture layer. We chose Chuanshi SH633, Grete GS1635R, and Wheeling HS5164SUMK and HS5164SBU as the four kinds of PDC drill bits, as well as the Kingdream HJ537GK roller-cone bit for comparison. When using a cone bit, the ROP was 2.16 m/h, RPM was 34 r/min, and MSE was 65.92 MPa, which was 39.13% the PDC. A higher ROP can be obtained at a lower mechanical speed. This shows that the HJ537GK cone bit [11] can be used in this formation and that the overall drilling effect is better than that of the PDC.

The 6th variable of the Xujiahe Formation is composed of coarse sandstone ranging from 3295–3330 m. The lithology of the 5th variable was significantly tapered. Its average drillability grade was 8.5, and the UCS of the rock was 80MPa, comprising a medium-hard texture layer. Using TORO RZ0475 cone bit is appropriate in theory; however, the actual ROP is not that high at an average of just 1 m/h. Observing the well history data, we found that the well leakage occurred at the drilling site and that the drilling fluid leakage was predominant. A diamond drill bit or impregnated drill bit [12–14], characterized by wear resistance, high strength, and impact resistance, can meet the plastic
deformation requirements of soft as well as hard staggered and soft mudstone in the Chuanshi I437 impregnated diamond (ID) bits.

The 3rd variable of the Xujiahe Formation consists primarily of shale at 3570–3740 m. The average drillability grade of the variable was 8.2, and the UCS of the rock was 180 MPa. The comparison between the Kingdream KPMD1642DRT compound drill bit and SH522 PDC bit shows that the KPMD1642DRT combined drill bit has approximately the same drilling rate as the SH522 bit, but with a lower mechanical speed. Therefore, it would appropriate to choose the KPMD1642DRT combined drill bits. The bits with lower MSE value demonstrate similar characteristics.

The 2nd variable of the Xujiahe Formation is 3740–3940 m, which is a set of thick sandstone strata whose lithology is thickened. The average drillability grade of the member was 8, and the UCS of the rock was 140 MPa, representing a hard formation. The comparison between the Chuanshi SH522 and Kingdream KPMD1642DRT combined drill bits revealed that the MSE of KPMD1642DRT combined drill bits decreased by approximately 23% compared with the SH522 drill bit and that the ROP was 2.75 m/h at an RPM of 31 r/min. Hence, the Kingdream KPMD1642DRT is suggested here.

5 Recommendations for bit selection

The suggestions for bit selection according to the results of bit evaluation and the mechanical characteristics of the formation rock are listed in Table 2.

Table 2. List of formation and recommended bit selection of the x-1 well

| Stratum          | Type  | Manufacturer | Model      |
|------------------|-------|--------------|------------|
| Da’anzhai        | PDC   | Chuanshi     | SH633      |
| Zhenzhuchong     | Cone  | Hanjiang     | HJ537GK    |
| Xu6              | ID    | Chuanshi     | I437       |
| Xu3              | CD    | Hanjiang     | KPMD1642DRT|
| Xu2              | CD    | Hanjiang     | KPMD1642DRT|

The Da’anzhai variable of the Ziliujing Formation uses Chuanshi SH633, which can be drilled quickly with a higher rotation speed and a lower drilling weight. It also has the advantages of low unit footage and high drill footage.

In the Zhenzhuchong variable of the Ziliujing Formation, the use of a roller-cone bit with shock, crushing and shear breaking rock is preferred. The Kingdream HJ537GK tri-cone bit is designed for middle and soft formations (hard shale, sandstone, soft limestone, mudstone, etc.) with relatively hard and abrasive intercalations; it cannot be used with high bit pressure and high rotation speed. This performance satisfies the drilling conditions of this formation.

The recommended Chuanshi I437 ID bits in the 3rd variable of the Xujiahe Formation adopts a B-shaped crown design and is suitable for hard formation. The distribution of different shapes of impregnated teeth is beneficial for a balanced wear. In addition, the design of a deep channel is beneficial to drilling performance and bit cleaning. The impregnated teeth are made of large-grain natural diamond processed by sintering and pressing. This has the advantages of fewer downhole accidents, fast speed, long service life, more footage, stable work, and good quality.

The Kingdream KPMD1642DRT combined drill bits used in the 3rd and 2nd variables of the Xujiahe Formation fully utilizes the advantages of the roller-cone bit and the PDC bit. The central position of the borehole is broken by the PDC cutter on the main cutter wing, whereas the drilling of the outer part
of the borehole is completed by the cutter and cutter wing. The rock-breaking difficulty of the outer part of the borehole is high, and the rock-breaking effect depends on the cooperation between the cutter and cutter wing. Hence, hard, abrasive formations and complex directional drilling operations are suitable for drilling shale and interactive formations.

6 Conclusion
By analyzing the drilling data, we can conclude that the stratum characteristics of the working area are as follows: sandstone and mudstone of different thicknesses are interbedded from top to bottom. In addition, as the rocks of the Xujiahe Formation are fine sandstone and siltstone, the formations are dense and have a certain degree of abrasiveness.

Through the calculation model of the rock mechanics parameters, the rock mechanics profiles of the strata in the work area are obtained. The distribution rules and characteristics of the parameters in the work area are also summarized. The rock strength and drillability grades of the Xujiahe Formation are high, with rock formation drillability ranging from 8–9. The numerical trend is consistent with the mechanical parameters, such as the elastic modulus, internal friction angle and cohesion, reaching a peak value at 2800–3000 m.

The MSE was employed to evaluate and analyze the drill bits used. The results, which show the effects of the drill bits, confirm that the MSE can better evaluate the performance of the drill bit in different formations and optimize the bit selection than other models.

7 Nomenclature

- $\mu_d$ - Poisson's ratio;
- $E$ - Elastic modulus, MPa;
- $V_p$ - Compressional wave velocities, m/s;
- $V_s$ - Shear wave velocities, m/s;
- $DEN$ - Rock density, g/cm$^3$;
- $\varphi$ - Internal friction angle, °;
- $C_o$ - Cohesion, MPa;
- $V_d$ - Clay content, %;
- $G$ - Select 2.0 in the old formation and 3.7 in new formation;
- $\Delta G$ - Correction factor for natural gamma rays;
- $GR$ - Natural gamma ray;
- $UCS$ - Uniaxial compressive strength, MPa;
- $AC$ - Acoustic time, $\mu$s/ft;
- $K_d$ - Rock drillability index;
- $K_{cd}$ - Rock formation drillability index;
- $\alpha$ - Biot coefficient;
- $P_d$ - Bottom-hole pressure, MPa;
- $P_p$ - Pore pressure, MPa;
- $CAI$ - Cerchar abrasion index;
- $M$ - Mechanical specific energy (MSE), MPa;
- $W$ - Weight on bit (WOB), KN;
$D_b$ - Diameter on bit, mm;
$r$ - Revolutions per minute, r/min;
$T_b$ - Torque on bit, KN·m;
$ROP$ - Rate of penetration, m/h;
$\mu$ - Coefficient of sliding friction.

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