Sand production prediction of deep gas wells in Bashijiqike Formation of the Keshen block

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Abstract: In order to effectively prevent the occurrence of sand production during the gas well production, rock mechanics tests were carried out for a deep tight sandstone gas reservoir in Bashijiqike Formation of the Keshen block, and the logging prediction models of mechanics parameters were established. At the same time, considering the effect of reservoir pressure and stimulation measures, based on the analysis of stress state of borehole wall and using M-C criterion, the calculation model of the critical production pressure of gas well was established to achieve the purpose of guiding production and improving the gas well production. The results show that the relationship between rock mechanic parameters with acoustic wave and volume density of the Bashijiqike Formation reservoir was studied, and the response mechanism of rock mechanics parameters was revealed, thus the logging calculation model of rock mechanics parameters was established. Based on the drilled fracturing and logging data, the multi-parameter prediction method of the formation pore pressure and the in-situ stress calculation model were established. The critical production pressure has also been significantly reduced, and the risk of sand production in gas wells increased significantly. After water immersion and acid fracturing, the compressive and elastic modulus of the rock samples decreased obviously, and the maximum decrease of the critical production pressure of the reservoirs in the study area reached 9 MPa. In order to ensure the safe production, it is necessary to supplement formation energy or take more effective sand control measures in the study area. The research results can provide guiding significance for gas well production allocation in this area.
Key Word: Bashijiqike Formation; Sand production prediction; Critical production pressure; Rock mechanics parameters

1. Introduction
In the production process of sandstone gas reservoir, sand control and production increase have always been a difficult contradiction to solve. Larger production pressure differential is needed to increase production [1-3], under higher production pressure differential conditions, the gas flow rate could increase. When the gas flow rate is higher than a certain value and rock particles are insufficient to be consolidated by the cementation strength of the rock matrix, the rock particles could fall off from the rock to increase the risk of sand production [4]. The normal production of gas well will be greatly negatively affected by the sand production of gas well, which can cause sand blockage of tubing, shortening the equipment maintenance cycle, and in serious cases, the gas wells can be shut in and the service life can be reduced.

In the industry, it is always the research hotspot to predict the sand production of oil and gas wells, which have many methods, including the on-site observation method, the empirical prediction method, the stress analysis method and the laboratory simulation method, etc [5-13]. The on-site observation method is limited to specific production areas, it can only qualitatively judge whether oil and gas wells are producing sand, and the reliability of sand production in formations with different rock strengths is low; The disadvantage of the empirical prediction method is that it requires a large amount of on-site production data and statistical analysis, such as sand production index method, sonic time difference method, formation strength method, dual parameter method and other empirical formulas to qualitatively predict the possibility of sand production in the reservoir, and the empirical formula method is convenient to apply, whereas it is limited by the formation, and not universal. The conclusion of the stress analysis method has a certain deviation from the actual conclusion due to the difference of the conditions which considered, thus the theoretical research needs to be further improved. The sand production prediction method proposed based on the rock strength criterion can comprehensively consider various factors affecting sand production and is a widely used method. With the development of oil and gas reservoirs, the risk of sand production in the oil and gas wells is aggravated with the decrease in formation pressure and the increase in water contents. And the influences of formation pressure, water content and other factors on the sand production have been researched by many researchers [14-17].

At present, the sand production of the deep gas wells in the Bashijiqike Formation of the Keshen block are serious. Seven of the production wells have been shut down due to serious sand production, and sand production has occurred during the production process of about 30 gas wells, indicating that the sand production of gas wells in the Keshen block is more serious. The decrease of formation pressure can change the in-situ stress state of the reservoir, affect the stability of the formation around the well, cause the change of the critical production pressure difference, thereby affect the sand production of the formation. At the same time, most of the gas wells in the Keshen block are acidified or acid-fractured...
before production, and most of the gas wells in the Keshen block have produced water in varying degrees. The mechanical properties of rock in the formation can be changed by the interaction of acid and rock or water soaking, thus, the stability of the formation can be affected and the critical production pressure differential can also change. At present, for the gas reservoirs of the Bashijiqike Formation in the Keshen block, there are few reports on the influences of the dynamic change of gas reservoir production, fracturing stimulation and later production water breakthrough on the critical production pressure differential of gas wells, which still need further study. Therefore, taking the Bashijiqike Formation in the Keshen block as the research object in this paper, logging prediction models for the rock mechanics parameters of the reservoir are built based on synchronous indoor physical experiments and rock mechanics experiments, and considering the dynamic change of formation pressure and the dynamic change of in-situ stress, combined with the effects of acid and water on the rock strength parameters, based on the Mohr Coulomb criterion, the critical production pressure differential of the gas reservoirs of Bashkiqik Formation in Keshen block is calculated, and the purpose of sand production prediction is achieved.

2. Reservoir geomechanical properties

2.1. Rock mechanical properties

The research scope of the reservoir geomechanical involves reservoir rock mechanics, formation pore pressure, in-situ stress and so on. The rock mechanical properties are the basis of the reservoir geomechanical. In order to better obtain the rock mechanics characteristics of reservoir section, it is necessary to establish the rock mechanics parameter profile of single well, which needs to establish the rock mechanics parameter calculation model based on logging information. At present, a large number of scholars have established empirical formulas for rock mechanical parameters of rocks in different areas and strata groups, whereas their application scope is limited. Therefore, it is necessary to establish a logging calculation model of rock mechanics parameters for the gas reservoirs of the Bashijiqike Formation in the Keshen block. Taking the rock samples of Bashijiqike formation as the research object, the basic physical properties of the rock samples are tested, and on this basis, the acoustic wave test is carried out to screen the rock samples, and then the acoustic wave and rock mechanics tests are carried out under the same conditions. The mechanical tests mainly include uniaxial compressive strength, Brazilian splitting test, etc.

Based on the indoor synchronous test results of rock physics and rock mechanics, the relationship between rock mechanics parameters, acoustic wave and bulk density of Bashijiqike Formation is studied, the response mechanism of rock mechanics parameters is revealed, and the logging calculation model of rock mechanics parameters can be established. The results are shown in Figure 1. It can be seen from Figure 1 that the uniaxial compressive strength of rock has a good negative correlation with P-wave time difference / density, and the exponential relationship can be seen in formula (1). The rock’s tensile strength and P-wave time difference/density have a good relationship for negative correlation, its exponential relationship can be seen in formula (2). There is a good correlation between dynamic elastic
modulus and static elastic modulus of rock, and the exponential relationship can be seen in formula (3). There is a good correlation between the dynamic Poisson’s ratio and the static Poisson’s ratio, and the logarithmic relationship can be seen in formula (4).

$$\sigma_c = 311.4 \times e^{-0.02 \times (AC/DEN)} , \quad R^2=0.7317 \quad (1)$$

Where $\sigma_c$ is the uniaxial compressive strength of rock, MPa; DEN is the formation density, g/cm$^3$; AC is the P-wave time difference, $\mu$s/ft.

$$\sigma_t = 97.308 \times e^{-0.089 \times (AC/DEN)} , \quad R^2=0.8457 \quad (2)$$

Where $\sigma_t$ is the tensile strength of rock, MPa.

$$E_s = 0.8735E_d + 1.1657 , \quad R^2=0.6459 \quad (3)$$

Where $E_s$ is the static elastic modulus of rock, GPa; $E_d$ is the dynamic elastic modulus of rock, GPa.

$$\mu_s = 0.8353\mu_d - 0.0662 , \quad R^2=0.647 \quad (4)$$
Where $\mu_s$ is the static Poisson's ratio of rock; $\mu_d$ is the dynamic Poisson's ratio of rock.

2.2. Formation pore pressure

The accurate prediction of formation pressure is of great significance for high-quality, efficient and safe drilling and reservoir fracturing. At present, there are many methods to predict formation pressure, among which the pore pressure prediction based on logging data is a common method. Based on logging data, this method can be roughly divided into three kinds, equivalent depth method, Eaton method, effective stress method, etc.. The former two methods need to establish normal compaction trend line, mainly considering the influence of single factor, such as acoustic wave, resistivity, gamma, etc., whereas the latter establishes the relationship between effective stress and logging rock physical response to predict formation pore pressure. This method comprehensively considers the influence of many factors, which can avoid the problems of low accuracy and large error caused by single factor[16]. Based on the measured data of formation pore pressure and logging data of corresponding well section, the effective stress calculation model is obtained:

$$
\sigma_e = 13.7350 \times DEPTH^{0.3059} + 4.7576 \times \ln(DT) - 7.8320 \times DEN - 3.7803 \times \ln(GR) - 126.8525
$$

(5)

Where $\sigma_e$ is the effective stress, MPa; Depth is the stratum depth, m; DT is the acoustic time difference, $\mu s$/ft; DEN is density, g/cm³; GR is natural gamma, API.

Through the effective stress calculation model obtained, the effective stress value calculated by the model is obtained based on the logging data, and compared with the measured effective stress (Figure 2), it can be seen that the calculated effective stress value is close to the measured effective stress value, and the model has high accuracy, meeting the engineering requirements. Based on the effective stress theory and density logging data, the formation pressure calculation formula of Wuerhe formation is as follows,

$$
P_p = \sigma_v - \sigma_e = \int_{H_0}^{0} \rho_0(h)gdh + \int_{H}^{H_0} \rho(h)gdh - \sigma_e
$$

(6)

Where $P_p$ is the formation pressure, MPa; $\sigma_v$ is the vertical stress, MPa; $H_0$ is the depth of logging starting point, m; $\rho_0(h)$ is the density of the unmeasured well section at point h, g/cm³; $\rho(h)$ is the logging density at depth h, g/cm³; g is the acceleration of gravity, kg·m/s², which can be taken as 9.8.
2.3. in-situ stress

The in-situ stress characteristics of reservoir are the basic parameters for drilling engineering and fracturing engineering, which are of great significance for oil and gas exploration and development in the research area. At present, there are many methods to determine the in-situ stress, among which the inversion calculation of in-situ stress based on hydraulic fracturing data is the most effective method for deep formation stress measurement, and it is also one of the main methods recommended by the International Testing Technical Committee for Rock Mechanics and Rock Engineering[18]. Based on the fracturing operation curve, the fracture pressure and closure pressure of the formation are obtained, and the minimum horizontal principal stress and maximum horizontal principal stress of the formation at a certain depth point are calculated[18]. On this basis, combined with the spring combination model (equation (7)), the tectonic strain coefficient of the depth point can be obtained, then the in-situ stress profile of a single well can be obtained. Based on the fracturing operation curve, the average values of the structural strain coefficients along the maximum principal stress direction and the minimum principal stress direction are $3.973 \times 10^{-3}$ and $3.84 \times 10^{-4}$ respectively, therefore, the in-situ stress profile of the reservoir can be calculated by using the spring combination model.

$$
\begin{align*}
\sigma_{H} &= \frac{\mu}{1 - \mu} \sigma_f + \frac{1 - 2\mu}{1 - \mu} \alpha \sigma_{\rho} + \frac{E}{1 - \mu} \varepsilon_{H} + \frac{\mu E}{1 - \mu^{2}} \varepsilon_{h} \\
\sigma_{h} &= \frac{\mu}{1 - \mu} \sigma_f + \frac{1 - 2\mu}{1 - \mu} \alpha \sigma_{\rho} + \frac{E}{1 - \mu} \varepsilon_{h} + \frac{\mu E}{1 - \mu^{2}} \varepsilon_{H} \\
\sigma_{\rho} &= \int_{H_{h}}^{H} \rho(h)gdh + \int_{H}^{H_{h}} \rho(h)gdh 
\end{align*}
$$

Where $\sigma_{H}$ is the maximum horizontal principal stress, MPa; $\sigma_{h}$ is minimum horizontal principal stress, MPa; $\alpha$ is the biot coefficient; $\varepsilon_{H}$ and $\varepsilon_{h}$ are the structural strain coefficients along the maximum principal stress direction and the minimum principal stress direction.
Based on the rock mechanics parameter calculation model, pore pressure calculation model and in-situ stress calculation model constructed above, combined with logging data, the geomechanical profile of single well Bashijiqike formation can be obtained, and the Figure 3 is the geomechanical parameter profile of a well. According to the calculation results of single well drilled in the research area, the uniaxial compressive strength, tensile strength, static elastic modulus, static Poisson's ratio, cohesive force and the internal friction angle of rocks in Bashijiqike formation are respectively mainly in the range of 96.99-188.23MPa, 4.24-11.25MPa, 21229.14-45869.45MPa, 0.31-0.33 and 11.29-28.81MPa, 10.33-26.02. The main distribution range of formation pressure in Bashijiqike formation is 1.62-1.87MPa/100m, the Bashijiqike formation is mainly of potential strike-slip type, and the vertical stress distribution range is 155.90MPa to 188.0MPa; the maximum horizontal in-situ stress ranges from 150.8Mpa to 206.3MPa; the minimum horizontal in-situ stress ranges from 114.6MPa to 174.5MPa.

![Figure 3. The geomechanical parameters profile of Bashijiqike Formation in well KS-1](image)

3. The influences of acidizing fluid and water soaking on rock strength

Based on the experimental research of the effects of acidizing and water soaking on the mechanical properties of rock samples from Bashijiqike formation, the effects of acidizing and water soaking on the critical production pressure differential of gas wells are investigated. The acidizing fluid is mainly composed of 5% hydrochloric acid according to the acidizing fluid formula in the acidizing or acid fracturing construction report. Rock samples of Bashijiqike formation are selected to study the influence of acid and water immersion on rock strength. According to the experimental stress-strain curve, the elastic modulus, Poisson's ratio, cohesion and internal friction angle of each core can be obtained, as shown in Figure 4. It can be seen from Figure 4 that the compressive strength and elastic modulus of the rocks showed a decreasing trend after the acid treatment or water immersion effect of the cores, and the Poisson's ratio and internal friction angle did not change significantly. The reduction of compressive
strength was about 7.1% after water immersion effect and about 15.4% after acid treatment; the reduction of elastic modulus was about 22% after water immersion effect and about 23% after acid treatment.

![Graph](image1)

**Figure 4.** Comparison of mechanical property parameters of cores before and after acid or water treatment

4. Sand production prediction

With the exploitation of gas reservoirs, the formation pressure drops and the formation stability becomes worse, which increases the risk of sand production in gas wells. When the critical production differential pressure is less than zero, the wellbore can be unstable and the formation sand production risk can be increased. However, when the critical production differential pressure is more than zero, the wellbore can be relatively stable and the formation sand production risk can be relatively small. This may be shown that the smaller the critical production differential pressure of the gas well, the greater the risk of wellbore instability and the greater the formation sand production risk. Based on the understanding of reservoir geomechanics and linear elasticity theory, Mohr Coulomb criterion is used to calculate the critical production pressure differential of Bashijiqike Formation in Keshen block, so as to carry out sand production prediction of the gas reservoirs of Bashijiqike Formation in Keshen block. Taking wells ks-2 and ks-3 as examples, the critical production pressure differential of Bashijiqike Formation is analyzed, and the calculation results are shown in Figure 5 to Figure 6. It can be seen from the figure that the critical production differential pressure of non-reservoir section decreases slightly with the formation pressure, while the critical production differential pressure of reservoir section decreases greatly with the formation pressure; under the initial formation conditions, the critical production pressure differential of some perforating sections corresponding to these wells is small, and some
sections have no critical production pressure differential, which indicates that the formation around the well is extremely unstable in the process of production, and the risk of sand production in the corresponding formation of these sections is obviously high; When the formation pressure coefficient decreases by 0.3 to 0.4, the critical production pressure differential of some well sections in the corresponding perforated section is low, and many well sections have no critical production pressure differential, which indicates that the formation around the well is extremely unstable in the production process, and the risk of sand production increases significantly. The reduction of converted formation pressure coefficient in the actual production process of these wells is more than 0.3, it shows that the sand production risk of these wells increases. At present, the production process of these wells has obvious sand production, but the sand production is not serious, probably because the liner injection completion has slowed down the degree of sand production. In the later production, it is still necessary to pay attention to the sand production phenomenon in the reservoir section, so as to carry out targeted sand prevention.

Based on the experimental results of acidizing fluid and water immersion effects, the critical production pressure differential of the Bashijiqike Formation is calculated for some of the producing gas wells in the Keshen block, and the calculated results of the KS-4 well are illustrated as an example, as shown in Figure 7. It can be seen from Figure 7 that after acid treatment, the critical production pressure differential of the reservoir section of the gas well shows a decreasing trend, and there is no critical production pressure differential in some well sections, which will aggravate the sand production of the gas well, and the maximum decrease of the critical production pressure differential of the reservoir section in the study area reaches 9 MPa. At the same time, after water breakthrough in gas well, the critical production pressure differential of reservoir section of gas well shows a decreasing trend, and there is no critical production pressure differential in some well sections, which will aggravate the sand production of gas well, and the maximum decrease of critical production pressure differential of reservoir section in the study area reaches 5MPa. This shows that after acidification and water breakthrough in gas well, the critical production pressure differential of formation shows a downward trend. As a result, there is no critical production pressure difference in some well sections, which could aggravate the sand production of gas wells, and lead to the need of supporting wellbore completion method in some well sections.
Figure 5. Critical production pressure differential profile of the Bashkichik Formation in well KS-2

Figure 6. Critical production pressure differential profile of the Bashkichik Formation in well KS-3
Figure 7. Critical production pressure differential profile of the Bashkichike Formation formation in well KS-4
5. Conclusion

(1) Based on the laboratory synchronous physical experiment and rock mechanics experiment, the logging calculation models of rock mechanics parameters of Bashijiqike Formation reservoir are established. Based on this, the pore pressure and in-situ stress calculation models are established for the gas reservoirs of the Bashkichiike Formation based on the fracturing and logging data.

(2) The compressive strength and elastic modulus of rock decrease after the action of acidizing fluid and water soaking, whereas Poisson's ratio and internal friction angle do not change obviously.

(3) As the formation pressure decreases, or after acid fracturing and water breakthrough in gas well, the critical production pressure differential presents a downward trend. As a result, there is no critical production pressure difference in some well sections, which could aggravate the sand production of gas wells, and lead to the need of supporting wellbore completion method in some well sections.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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