Application of Bowers Model in Abnormal Pore Pressure Prediction in Deepwater Drilling

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Abstract. Accurate prediction of formation pore pressure is of great significance to ensure drilling safety. Most of the traditional pore pressure analysis methods are based on the theory of unbalanced compaction of mudstone, and theoretically, only the abnormally high pressure formed during “loading” process can be predicted. The Bowers model is based on the effective stress principle, and can be used for most pore pressure prediction in different lithology and pressure mechanism. The Bowers model was used to analyse the abnormal formation pressure in deep-water area of the Q Basin, South China Sea. According to logging data and pressure test data of drilled wells, it was judged that the cause of abnormal pore pressure in the above area is both “loading” and “unloading” mechanism and the empirical coefficients of the Bowers model in this region were calculated. Using seismic interval velocity data, the pore pressure of an exploration well was predicted before drilling and the prediction error is less than 5% compared with the measured values after drilling. It is shown that the Bowers model has high accuracy for quantitative prediction of abnormal pore pressure in deep-water area of the Q basin.

1. Introduction

Prediction of formation pore pressure is an important task in oil and gas exploration and development, and accurate prediction of pore pressure determines whether the drilling engineering can be carried out smoothly. Research shows that the formation mechanism of abnormally high pore pressure is mainly composed of unbalanced compaction, structural extrusion, hydrocarbon generation pressurization and fluid thermal expansion [1]. Traditional methods of pore pressure prediction are mainly based on the normal compaction trend of formation, which belongs to empirical and semi empirical methods. The main drawbacks are that the establishment of normal compaction trend line and the selection of some parameters are based on the experience of the analyst, and these methods are not suitable for detecting pore pressure of other lithology except mudstone and detecting abnormal pore pressure outside the unbalanced compaction mechanism. The representative of such methods is the Eaton model based on interval transit time logging or seismic interval velocity data [2-4]. In order to compensate for the shortcomings of traditional prediction methods, Glenn Bowers proposed a pore pressure calculation method based on the effective stress theory, the Bowers model, which divides the main mechanism of abnormal high pressure formation into two types according to effective stress loading and unloading, and establishes loading and unloading curves to reflect the relationship between effective stress and acoustic velocity. According to the relationship, vertical effective stress can be calculated directly using measured or predicted acoustic velocity, and the pore pressure can be calculated by the effective
stress principle [5]. Theoretically, the Bowers model can be used for abnormal high pressure prediction with different lithology and different pressure forming mechanisms.

2. The Bowers model for pore pressure prediction

The Bowers model uses acoustic velocity to obtain vertical effective stress, and then subtracts the vertical effective stress from overburden pressure to obtain formation pore pressure. In the Bowers model, the anomalous high pressure prediction caused by unbalanced compaction requires only two empirical parameters, which can be determined by the actual pressure data of drilled wells in the same block or adjacent blocks.

The prediction of abnormal pore pressure caused by hydrocarbon generation, hydrocarbon migration or fluid expansion requires more information and parameters. In these cases, vertical effective stress in the process of abnormal high pressure formation is decreasing, that is, in the “unloading” state. Using the Bowers model to analyse the abnormal pressure caused by “unloading” mechanism, it is necessary to determine the maximum effective stress value (\( \sigma_{\text{max}} \)) of the formation history and establish an effective stress state that reflects the “unloading” velocity of the formation, and a total of four experience parameters need to be identified.

The Bowers model of pore pressure prediction mainly uses the propagation velocity of acoustic wave in formation. Before calculation, the abnormal pore pressure mechanism should be judged as “loading” or “unloading” based on the cross-plot of acoustic velocity and density data. If the P-wave velocity and the density become smaller at the same time of a point in formation, that is, from point C to point B in figure 1, the pressure forming mechanism is “loading” type. If the P-wave velocity decreases in the abnormal high pressure interval, and the density remains essentially unchanged, that is, from point C to point D in figure 1, the pressure forming mechanism is “unloading” type [6].

Fig. 1. Schematic diagram of the Bowers method for judging abnormal high pressure mechanism.

For abnormal pressure caused by loading mechanism, the pore pressure is predicted by the following equation:

\[
p_p = \sigma_v - \left( \frac{V - V_{ml}}{A} \right)^{(1/B)}
\]  

(1)

For abnormal pressure caused by unloading mechanism, the pore pressure is predicted by the following equation:

\[
p_p = \sigma_v - \left( \sigma_{\text{max}} \right)^{(1-U)} \left( \frac{V - V_{ml}}{A} \right)^{(U/B)}
\]  

(2)
In the above formulae, $p_p$ is pore pressure; $\sigma_y$ is total vertical stress of overburden formation; $V$ is formation P-wave velocity; $V_{so}$ is the P-wave velocity of surface or seabed; $\sigma_{\text{max}}$ is the maximum effective stress the formation has ever experienced; $A$, $B$, $U$ are experience factors.

If the historical maximum P-wave velocity ($V_{\text{max}}$) can be get through data analysis, the corresponding $\sigma_{\text{max}}$ can be calculated by the following formula:

$$
\sigma_{\text{max}} = \left( \frac{V_{\text{max}} - V_{\text{so}}}{A} \right)^{(\frac{1}{U})}
$$

(3)

It can be seen that if the coefficient $U$ is equal to 1, the equation (2) degenerates into equation (1), indicating that the stratum has no “unloading” effect. If the formation has “unloading” process, the coefficient $U$ is greater than 1.

The Bowers method is suitable for a wide range, but the parameters in the prediction equation can only be accurately determined in the case of a comprehensive and clear understanding of the stress history of formation, so the detail level of data is more demanding.

3. Application in deepwater drilling

The sedimentary in the Q basin of the South China Sea has formations of Yacheng, Lingshui, Sanya, Meishan, Huangliu, Yinggehai and Ledong groups from bottom to up. Several oil-bearing structures have been discovered in the central depression zone at a water depth of 1300-2200m, and found a high quality and high production gas field in the L17 structure [7]. It has been proved from drilled exploration wells that the formation above 3000m in the Q basin are basically normal pore pressure, and the abnormally high pore pressure is mainly distributed in the formation of the Miocene Huangliu and Meishan groups, and the Oligocene Lingshui group. According to the geological data, the Q basin is a typical extensional basin, which is controlled by the expansion of the South China Sea. The faults have strong sealing, and the overpressure system is not timely pressure relief, which is precondition of the abnormal pore pressure in the basin [8, 9].

3.1. Formation mechanism of abnormal pressure

According to the judgment method of abnormal high pressure formation mechanism proposed in the Bowers model, the pore pressure formation mechanism of the Q basin was analysed by using logging data. The cross plots of density and P-wave velocity of L22 and Y19 blocks are shown in figure 2 and figure 3 respectively, where the buried depth of the Yinggehai, Huangliu, Meishan, Sanya, Lingshui and Yacheng groups increased in turn. According to the data, the variation trend of density and acoustic velocity of these two blocks basically conform to the normal compaction trend line, so the abnormal high pressure below the Huangliu group is mainly caused by the “loading” mechanism. In block L22, the data of Meishan group deviate slightly from the compaction trend, so the stratum is also affected by “unloading” mechanism. From the overall data analysis, “loading” effect is the main cause of abnormal high pressure, which is consistent with conclusions of the relevant geological research in this area [10, 11]. Therefore, considering the effects of loading and unloading mechanisms, the Bowers model is more suitable for abnormal pore pressure prediction of the Q basin.
3.2. Abnormal pore pressure prediction

Using the Bowers model to analyse and predict the formation pressure, the overburden pressure must be calculated firstly. For deep water drilling, considering the impact of water depth and rotary height, the overburden pressure at the depth $H_2$ below the seabed can be calculated by the following equation.

$$\sigma_v = \rho_w g H_1 + \int_{H_1}^{H_2} \rho_r g dh$$  \hspace{1cm} (4)

Where, $\rho_w$ is the density of sea water; $\rho_r$ is the density of formation; $g$ is the gravitational acceleration. $H_1$ is the water depth; $H_2$ is the depth below the sea level.

Based on the density log data, the variation laws of overburden pressure with depth in block L22 and Y19 were calculated. The overburden pressure calculation results, the formation pore pressure test results of exploratory wells and the hydrostatic pressure curve are plotted on the same chart as shown in figure 4.
Fig. 4. Comparison chart of overburden pressure, hydrostatic pressure and measured pore pressure.

It can be seen that the measured pore pressure is slightly higher than the hydrostatic pressure. According to the Bowers model, the difference between overburden pressure and pore pressure can be expressed by the following equation.

\[
\sigma_v - p_p = \left( \frac{V - V_{ml}}{A} \right)^{1/B}
\]

(5)

Take logarithm on both sides of the equation.

\[
\ln \left( V - V_{ml} \right) = B \ln \left( \sigma_v - p_p \right) + \ln A
\]

(6)

According to the acoustic time difference logging data, the overburden pressure and the measured pore pressure of the two wells Y19-1 and L22-1, and the wave velocity at the seabed is 1500 m/s, the relationship between the acoustic velocity difference and the effective stress was plotted, as shown in figure 5. By linear fitting, the coefficients A and B are respectively 141.2 and 0.81.

Fig. 5. The relationship between the acoustic velocity difference and the effective stress.

According to the previous analysis, the “unloading” effect is not obvious in the pressure forming mechanism of Q basin. For the strata affected by unloading, the coefficient U is set to 3.0, and the historical maximum acoustic velocity is assumed to be 1.1 times of the current value. The pore pressure curves of well Y19-1 and well L22-1 were calculated by using well logging data and the Bowers model, and compared with the measured pore pressure, as shown in figure 6. The comparison
results show that the calculated pore pressure is in good agreement with the measured values, and the Bowers model is suitable for the analysis and prediction of abnormal pore pressure in the deep water area of Q basin.

![Comparison of calculated and measured pore pressure](image)

Fig. 6. The comparison of calculated and measured pore pressure of well L22-1 and well Y19-1.

Therefore, the formation pressure of the exploration well in block L17 was also predicted by using the Bowers model according to the seismic interval velocity data before drilling, as shown in figure 7. It can be seen from the figure that the measured seismic interval velocity below 2750 m is significantly different from the velocity trend line calculated by Bowers model when the formation is assumed to be normal pressure. The prediction results of the pore pressure variation law in well L17-1 show that the formation above 2750 m is under normal pressure, and the pore pressure in the formation below 2750 m gradually increases, and the equivalent density of formation pressure reaches about 1.30 g/cm³ in 3600m.
3.3. Prediction result evaluation

The comparison between the predicted pore pressure before drilling and the measured results after drilling and the drilling fluid density in well L17-1 is shown in figure 8. The actual density of drilling fluid is 1.08-1.33 g/cm³. The drilling process is smooth, there are no complicated problems such as overflow and surge, and the non-production time only accounts for 2% of the total time. Compared with the actual measured pore pressure, the pre-drilling pressure prediction error is less than 5%, indicating that the Bowers model has a good accuracy in predicting pore pressure, which can guide the design of drilling fluid density.

4. Conclusions

(1) Bowers model can be used for the analysis of abnormal pore pressure in different lithology and caused by different pressure mechanism, which has certain advantages over conventional pore pressure prediction methods.

(2) According to the comparison of acoustic velocity and density data of drilled wells in deep water of Q basin in the South China Sea, the formation mechanism of abnormal pore pressure in this area is
mainly of the “loading” type, and some strata are affected by “unloading”, which is suitable for analysis using the Bowers model.

(3) Based on the Bowers model, the pore pressure longitudinal profile of an exploratory well in the L17 block was predicted before drilling, and the predicted value, measured value and actual drilling fluid density were compared after drilling, indicating that the relative error of prediction before drilling was less than 5%. The Bowers model can be used to accurately predict the formation pore pressure in the deep water area of the Q Basin.

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