In situ stress distribution and its impact on CBM reservoir properties in the Zhengzhuang area, southern Qinshui Basin, North China

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\textbf{ABSTRACT}

\textit{In situ} stress is crucial for hydraulic fracturing during enhanced coalbed methane (CBM) recovery. The study is an attempt to get a better idea of fine evaluation of the stress distribution, and to clarify the stress distribution near the fault zone. The \textit{in situ} stresses and formation pore pressure of coal seams at depths of 300–1300 m in the Zhengzhuang area of the southern Qinshui Basin were systematically analysed using well test data. The research area was divided into three partitions based on formation pore pressure gradient and regional geological structure. The three partitions present various petrophysical properties. Moreover, a 3D simulation was conducted to evaluate the effects of faulting on the stress state. Excellent relations exist among the pore pressure, minimum horizontal stress ($P_h$ and $\sigma_h$) and depth of the target coal seam, which can be used to predict the distribution of \textit{in situ} stresses in the research area where few well test data exist. A lower lateral stress coefficient ($\kappa_l$) suggests a higher permeability in the extensional southern Qinshui Basin. Lower horizontal tectonic stress coefficients and relative stress factors suggest a higher permeability area. The simulation and microseismic fracture monitoring results show that the horizontal principal stress direction obviously changes near the fault zone, suggesting the existence of a complex \textit{in situ} stress state. Faulting has a great influence on $\sigma_h$ orientation. The stress simulation could be a means to detect faults and predict the direction and magnitude of $\sigma_h$ for areas without adequate well test data. Therefore, these results may have significant implications for the permeability evaluation of coal seams during safety mining and CBM production.

1. Introduction

For a long time, \textit{in situ} stresses have been widely used to estimate reservoir properties and are indispensable in coalbed methane (CBM) development (Finkbeiner et al., 1997; Gentzis, 2009; Chatterjee and Pal, 2010; Chen et al., 2018). The magnitude of porosity and permeability in coal reservoirs can be used to directly determine CBM accumulation and development (Moore, 2012; Zhang et al., 2016). \textit{In situ} stresses have a direct influence on the petrophysical properties (e.g., lithology, porosity, permeability and density) of coal reservoirs (Pan et al., 2010; Connell et al., 2010; Zhang et al., 2016), which is the key to evaluating coal-bearing strata. Many studies on the southern Qinshui Basin (SQB) have been conducted by many scholars (Cai et al., 2011; Meng et al., 2011; Chen et al., 2015; Liu et al., 2016), where the \textit{in situ} stress distribution, porosity and permeability have been well discussed. Meng et al. (2011) found that the reservoir permeability decreases markedly with increasing \textit{in situ} stress in the SQB. The CBM reservoir permeability is generally lower than 1 mD in the SQB (Cai et al., 2011), which was mainly inferred from mineralization, low porosity and strong tectonic stress. Recently, Liu et al. (2016) evaluated the stress data in the SQB and concluded that permeability distinctly decreases as $\sigma_3$ increases. The stress orientation is also very important to reservoir permeability. The \textit{in situ} stress orientation is determined using borehole imaging data (Kingdon et al., 2016; Liang et al., 2018). For a study area with few borehole imaging data, other methods can also be applied to determine the horizontal principal stress orientation (Mallik et al., 2008; Paul and Chatterjee, 2011a; Li et al., 2016; Liu et al., 2016). The Electromagnetic Radiation (EMR) technique was adopted by Mallik et al. (2008) to determine the principal horizontal stress directions in the eastern Kachchh. The cross-dipole data were used by Li et al. (2016) to evaluate the horizontal principal stress. Moreover, the direction of fractures and $\sigma_3$ and $\sigma_h$ were compared, which proved that the fracture...
direction could be considered reliable evidence for $\sigma_H$ direction (Brudy and Zoback, 1999). Previous research (Paul and Chatterjee, 2011a, b; Liu et al., 2016) also confirmed that fracture direction is in accord with the orientation of $\sigma_H$. Although many studies related to the Zhengzhuang area have been conducted (Chen et al., 2015; Huang et al., 2015; Wang et al., 2016a, b; Li et al., 2016), no scholars have specifically focused on studying the in situ stress in this area. Furthermore, the faulting affecting the stress pattern was not elaborated in the above studies.

It is hard to predict the complex stress state by using the conventional study methods (e.g., hydraulic fracturing method) especially considering the faults. The finite element method (FEM) is an effective method used to simulate the complex stress state. The 3D FEM has been adopted to evaluate stress near faults (Maerten et al., 2006). In addition, a 3D model was established for the faulted strata by Chatterjee (2008) to study the effects of faulting on the stress state, and the stress orientation implications for the basin structure were discussed. A finite element (FE) code and a finite difference (FD) code were combined by Meng and Wang (2018) to study fault rupture and ground motion.

Therefore, the FEM has been applied by using the finite element software Workbench 15.0 in this paper.

In situ stresses are evaluated and forecasted by using the field data of 22 CBM wells. The effects of horizontal principal stresses and pore pressure on permeability and porosity are discussed in different partitions. The microseismic data, which are adopted by monitoring fracture during hydraulic fracturing, have been analyzed to obtain the direction of horizontal principal stresses. The Zhengzhuang area has experienced multi-period tectonic stresses and the formation of a few normal faults, leading to a complex stress state (Teng et al., 2015; Wang et al., 2016a, b), therefore, a 3D FEM model should be established to evaluate the stress distribution near the faults and discuss the effects of normal faults on in situ stresses.

This study provides an attempt to analyze in situ stress in the Zhengzhuang area and its relation with CBM reservoir properties. Firstly, the permeability, porosity and in situ stress have specific variations in different partitions, which will be elaborated. Secondly, the lateral stress coefficient ($\kappa$) will be used to discuss its relation with permeability, which has an important significance to predict the high

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**Fig. 1.** Location and geological structure of the Zhengzhuang area in the SQB, North China.
permeability zone. Finally, the above relations between in situ stress and reservoir properties could be used to guide the optimization of hydraulic fracturing.

2. Geological settings

The Zhengzhuang area is located in the SQB, which is one of the largest coal-accumulating basins in the world and is surrounded by Taihang Mountain, Huo Mountain, Wutai Mountain, and Zhongtiao Mountain (Su et al., 2005; Cai et al., 2011; Zhang et al., 2015). The tectonic structure in the study area is relatively stable (Li et al., 2011). The Houchengyao and Sitou faults are located in the S-E edge of the study area (Fig. 1). The Shanxi and Taiyuan Formations are the two main coal-bearing strata (Lv et al., 2012). The No. 3 coal seam of the Shanxi Formation, with thicknesses of 3–7 m, has high gas content and is important for CBM development (Teng et al., 2015). The burial depth, which increases near the Sitou fault, mainly ranges from 300 to 1300 m in the No. 3 coal seam. The maximum vitrinite reflectance (Ro, m) for the No. 3 coal seam changes between 3.51% and 3.69%, which is anthracite (Li et al., 2016). Young’s modulus, Poisson’s ratio and density of the No. 3 coal range from 0.21 to 1.6 GPa, 0.28 to 0.33 and 1.47–1.60 g/cm³, respectively. The study area first experienced N-S principal compressive stress during the Indosinian period (∼250 Ma). Then, during the Yanshan period (∼208 Ma), the NW-SE principal compressive stress formed the basic structural framework and sedimentary background of the study area (Wang et al., 2016a, b). NNE–SSW compression stress occurred during the Himalayan period (∼65 Ma), leading to a few secondary folds striking N-W due to nearly horizontal compressive stress (Liu et al., 2013; Su et al., 2005; Qin et al., 2008; Cai et al., 2011).

3. Methodology

3.1. The in situ stress, formation pore pressure and permeability

The injection/falloff test is the main CBM well test method being used, as shown in Fig. 2a. The injection/falloff test is an effective and common way to estimate CBM reservoir properties, including permeability and pore pressure (Hopkins et al., 1998). The injection/falloff tests in the Zhengzhuang coal reservoir are as follows: the water is injected into the tubing at a stable injection rate for 12 h during the injection test, and then, the well is closed for 24 h, and the pressure is recorded by an electronic pressure gauge. The typical measurement pressure and time curve of injection/falloff test are presented in Fig. 2b. The cumulative injection amount is 0.092 m³, and the average discharge is ~0.184 m³/day. The reservoir pressure/temperature and permeability are obtained according to the injection/falloff well test data. The hydraulic fracturing (HF) method is an effective way to measure in situ stresses (Haimson and Cornet, 2003; Zhang and Roegiers, 2010). The HF test is conducted to obtain the shut-in pressure $\sigma_h$. Fig. 2c shows a typical curve of pressure vs. time for the in situ stress test. There are a total of four cycle tests, and each cycle takes 0.6 h to complete. The data of two or three cycles are chosen and then averaged to obtain the shut-in pressure. Finally, the well test data are analysed, and the permeability, formation temperature, formation pore pressure ($P_p$), breakdown pressure ($P_b$), and shut-in pressure ($P_s$) are obtained.

### Table 1

<table>
<thead>
<tr>
<th>Well no.</th>
<th>$P_o$ (MPa)</th>
<th>$P_{on}$ (MPa)</th>
<th>$\varepsilon$ (%)</th>
<th>Compaction degree</th>
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</thead>
<tbody>
<tr>
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<td>6.40</td>
<td>−43.90</td>
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<td>4.69</td>
<td>−25.59</td>
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</tr>
<tr>
<td>ZS13</td>
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<td>6.39</td>
<td>−20.69</td>
<td></td>
</tr>
<tr>
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<td>6.84</td>
<td>−19.20</td>
<td></td>
</tr>
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<td>−14.84</td>
<td></td>
</tr>
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<td></td>
</tr>
<tr>
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<td>8.16</td>
<td>−7.97</td>
<td></td>
</tr>
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</tr>
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</tr>
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<td>Normal compaction</td>
</tr>
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<td>−2.03</td>
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</tr>
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</tr>
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</tr>
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</tr>
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</tr>
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<td>Overcompaction</td>
</tr>
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</tr>
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<td>5.81</td>
<td>7.91</td>
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</tr>
<tr>
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<td>15.76</td>
<td></td>
</tr>
<tr>
<td>ZS22</td>
<td>10.60</td>
<td>9.03</td>
<td>17.34</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. (a) Schematic of typical injection/falloff and HF test equipment. (b) Typical measurement pressure and time curve of the injection/falloff test (well ZS15). (c) Typical curve of pressure vs. time for in situ stress test (well ZS15).
The $\sigma_h$ is obtained by the following:

$$\sigma_h = P_i$$

(1)

The calculation method of $\sigma_h$ was suggested by Haimson and Fairhurst (1970):

$$\sigma_H = 3\sigma_o - P_h - P_o + T$$

(2)

Then, modified by Zhang and Roegiers (2010) for a vertical borehole, the Biot effective stress coefficient should be considered to calculate the $\sigma_H$:

$$\sigma_H = 3\sigma_o - P_h - \alpha P_o$$

(3)

The reopening pressure $P_r$ has the following relation:

$$P_r = P_b - T$$

(4)

Combining Eqs. (3) and (4), $\sigma_H$ is acquired:

$$\sigma_H = 3\sigma_o - P_h - \alpha P_o + T$$

(5)

The overburden stress is obtained by the following:

$$\sigma_r = \int_0^D \rho(D) g dD$$

(6)

where $P_i$ is the measured average shut-in pressure, $P_h$ is the breakdown pressure and $P_o$ is the formation pore pressure, $T$ is the tensile strength.
of the coal seam, $P_r$ is the reopening pressure, $\alpha$ is the Biot effective stress coefficient, $\rho$ is the density of the overlying strata and $D$ is the depth of the target coal seam.

### 3.1.1. Formation pore pressure partition

The overpressures are classified into three categories worldwide, including mild (11.5–14.0 MPa/km), moderate (14.0–17.0 MPa/km) and high (>17.0 MPa/km) (Tingay et al., 2009). The concept of overpressure (absolute value above the hydrostatic pressure) and underpressure (absolute value below the hydrostatic pressure) has been defined at the burial depth of the target strata (Mudford, 1988; Hunt, 1990; Dasgupta et al., 2016). The average formation pore pressure gradient is 9.1 MPa/km in the Zhengzhuang area, far below 11.5 MPa, which is in the undercompaction state compared with the theoretical hydrostatic pressure of 9.8. Based on pore pressures from a well test of 22 exploration wells, the reservoir compaction in the Zhengzhuang area is classified as follows: 1) undercompaction ($\epsilon < -4\%$), 2) normal compaction ($-4\% < \epsilon < 4\%$) and 3) overcompaction ($\epsilon > 4\%$), as shown in Table 1. The relative compaction rate ($\epsilon$) is introduced as follows:

$$\epsilon = \frac{P_o - P_{on}}{P_{on}}$$  \hspace{1cm} (7)

where $P_o$ is the actual formation pore pressure from the well data, $P_{on}$ is assumed to be equal to the hydrostatic pressure, which is equal to the equivalent fluid column pressure:

$$P_{on} = \rho_0 g D$$  \hspace{1cm} (8)

$P_{on}$ is the theoretical hydrostatic pressure; $\rho_0$ is the density of water. Combining the reservoir compaction with the structural elevation of the No. 3 coal seam, the research area was divided into three partitions. Fig. 3 shows that the partitions include parts A, B and C. The rectangle height represents the value of the relative compaction rate ($\epsilon$). The relations between the in situ stress and porosity-permeability in the No. 3 coal seam will be elaborated below for different partitions.

### 3.1.2. Tectonic stress coefficient and the relative stress factor

The combined in situ stress model (Eqs. (9) and (10)) is one of the classic in situ stress models, which is established on the condition that the reservoir is a kind of homogeneous and isotropic, linear elastic material, and the model assumes that the reservoir horizontal strain is a constant. Although the coal is anisotropic, physical properties that change slightly in the horizontal and vertical directions of the thin coal seam (average thickness of 5.5 m in the Zhengzhuang area according to Wang et al., 2016a, b), it can be considered homogeneous. Horizontal tectonic stress coefficients were introduced, which can reflect the influence of tectonic stress on the in situ stress. Combining Eqs. (9) and (10) with Eqs. (1) and (5), the maximum/minimum horizontal tectonic stress coefficients ($\xi_h$, $\xi_v$) were calculated (Najibi et al., 2017; Ostadhassan et al., 2012).

$$\sigma_h = \frac{\mu}{1 - \mu} (\sigma_v - \alpha \sigma_h) + \alpha \sigma_v + \frac{E}{1 - \mu^2} \xi_h$$  \hspace{1cm} (9)

$$\sigma_v = \frac{1}{1 - \mu} (\sigma_v - \alpha \sigma_h) + \alpha \sigma_v + \frac{E}{1 - \mu^2} \xi_v$$  \hspace{1cm} (10)

where $\mu$ is Poisson’s ratio. $\sigma_{hi}$ is equal to $\sigma_h$ in the Anderson in situ stress model (Anderson, 1951) without considering tectonic stress (Eq. (11)). Therefore, the horizontal stresses mainly originate from the overburden weight.

$$\sigma_{vi} = \sigma_v = \frac{\mu}{1 - \mu} (\sigma_v - \alpha \sigma_h) + \alpha \sigma_v$$  \hspace{1cm} (11)

To evaluate the influence of tectonic stress on the in situ stress, the relative stress factor ($\phi$) was proposed and defined by the ratio between the difference (Eqs. (1) and (5)) subtract Eq. (11) and the Anderson in situ stress model (Anderson, 1951). The maximum horizontal relative stress factor ($\phi_{hi}$) and the minimum horizontal relative stress factor ($\phi_{vi}$) can be acquired as follows:

$$\phi_{hi} = \frac{3\sigma_{hi} - P_h - \alpha \sigma_v + T - \left(\frac{\mu}{1 - \mu} (\sigma_v - \alpha \sigma_h) + \alpha \sigma_v\right)}{3\sigma_{hi} - P_h - \alpha \sigma_v + T}$$  \hspace{1cm} (12)

Fig. 5. Three-dimensional model constructed from the strata evolution and geophysical well-log data showing four lithologic layers. (a) The red outline shows the simulation area. (b) Vertical and horizontal stresses are applied to the model boundary. (c) The side face of the 3D model, including the size, and the four lithologic layers are marked out. (d) Enlarged view near the faults.

### Table 2

Rock properties used in the 3D FEM for the Zhengzhuang area.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>Average density (kg/m$^3$)</th>
</tr>
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<tr>
<td>1</td>
<td>1.12</td>
<td>0.32</td>
<td>1535</td>
</tr>
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<td>2</td>
<td>0.21</td>
<td>0.33</td>
<td>1570</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>0.21</td>
<td>2620</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>0.21</td>
<td>2620</td>
</tr>
</tbody>
</table>
Table 3
Injection/falloff, in situ stress test parameters and logging data of the No. 3 coal seam in the Zhengzhuang area.

<table>
<thead>
<tr>
<th>Partition</th>
<th>Well no.</th>
<th>Depth (m)</th>
<th>DTC</th>
<th>DTS</th>
<th>E (MPa)</th>
<th>μ</th>
<th>ρ₁ (g/cm³)</th>
<th>α</th>
<th>ɸ (%)</th>
<th>k (mD)</th>
<th>P₀ (MPa)</th>
<th>Temp (°C)</th>
<th>Pₛ (MPa)</th>
<th>Pₛ (MPa)</th>
<th>σ₁ (MPa)</th>
<th>σ₂ (MPa)</th>
<th>σ₃ (MPa)</th>
</tr>
</thead>
<tbody>
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<td>A</td>
<td>ZS1</td>
<td>1242.40</td>
<td>462.45</td>
<td>830.00</td>
<td>1120</td>
<td>0.33</td>
<td>1.50</td>
<td>0.733</td>
<td>4.10</td>
<td>0.047</td>
<td>10.53</td>
<td>38.65</td>
<td>27.65</td>
<td>29.45</td>
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<td></td>
<td>ZS2</td>
<td>1122.30</td>
<td>415.00</td>
<td>690.00</td>
<td>820</td>
<td>0.32</td>
<td>1.53</td>
<td>0.835</td>
<td>4.11</td>
<td>0.013</td>
<td>10.08</td>
<td>35.37</td>
<td>26.40</td>
<td>27.74</td>
<td>44.38</td>
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<td>27.50</td>
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<td>ZS3</td>
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<td>419.77</td>
<td>706.27</td>
<td>710</td>
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<td>1.58</td>
<td>0.853</td>
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DTC is compressional wave slowness, DTS is shear wave slowness, E is Young's modulus, μ is Poisson's ratio, ρ₁ is coal density and ɸ is porosity.
unconventional oil/gas field (Wang et al., 2016a, b). The in situ stress field will change during HF, leading to tangential dislocation of the fractures in the reservoir, thus producing microseismic waves (Anderson and Johnson, 1999; Ju et al., 2017). Therefore, the microseismic waves were monitored and interpreted to characterize the fractures. The monitoring formation is P1s with an average burial depth of 300–1300 m in the Zhengzhuang area. A schematic diagram (well ZS11) of monitoring hydraulic fractures and in situ fractures is presented in Fig. 4. The coloured dots in Fig. 4a indicate the locations of microseismic events, which clearly show that the hydraulic fractures are mainly concentrated near the wellbore. The dots in Fig. 4b represent the in situ fractures, which are detected by monitoring fracturing fluid leakage. The directions of in situ fractures are consistent with the directions of hydraulic fractures.

3.2. The in situ stress numerical simulation

A 3D model has been used to verify the modelling method (Chatterjee, 2008). The stress state of elements in the model was defined by Huang et al. (2017). The model was established and the output data of numerical analysis was finished using ANSYS workbench 15.0. The fine mesh was used near the fault zone to keep the simulation accuracy. All loadings including \( \sigma_H \), \( \sigma_h \) and \( \sigma_v \) were applied on the surfaces of the model (Fig. 5b). Displacement in each element was constrained along the directions of loading direction. The actual size of the research area was considered to simulate the formation. As mentioned in section 3.1.2, the coal seam was deemed as homogeneous. The

### Eq. (13)

\[
\phi_h = \frac{P_o - \left( \frac{\mu}{1-\nu} (\sigma_h - \alpha P_o) + \alpha P \right)}{P_o}
\]
simulation area is shown in Fig. 5 and includes the Houchengyao and Sitou faults. Rock mechanic properties are adopted by different strata in this model. The roof and floor of the No. 3 coal seam consist mainly of mudstone and sandstone (Wang et al., 2016a, b). The rock properties of the coal seam depend on the distance from the fault. The strata in the Zhengzhuang area have an average dip of 4° (Teng et al., 2015), thus, the model is established with horizontal layers with four rock property types (Fig. 5 and Table 2). Layers 1 and 2 are the coal seams with the thickness of ~5 m. In addition, the layer 2 is located in the fault zone. Layers 3 and 4 have the same mechanical properties and are the roof and floor rocks, respectively. The loading data are obtained from the calculation of in situ stresses. The top vertical stress is set using the standard Earth gravity value. The magnitude of vertical stress, applied at the bottom face of the 3D faulted model, is calculated by the overburden loads. The calculated value is 32 MPa. The average \( \sigma_h \) values loading at the front and back surfaces of the 3D model are 16.55 MPa (0–750 m, layer 3), 27.65 MPa (750–755 m, layer 1), 35 MPa (755–1250 m, layer 4), 20.23 MPa (0–1000 m, the roof stratum in the fault zone), 35 MPa (1000–1005 m, layer 2) and 38.68 MPa (1005–1250 m, the floor stratum in the fault zone). Similarly, the average \( \sigma_h \) values acting at the left and right surfaces are 9.27 MPa (0–750 m, layer 3), 16.40 MPa (750–755 m, layer 1), and 21.12 MPa (755–1250 m, layer 4). The friction coefficient as the integral parameter for normal faulting has been calculated as 0.6, which has been used for normal faulting in the K-G basin (Gowd and Rao, 1992). Previous work (Meng et al., 2011) also indicated that Anderson’s faulting theory with a friction coefficient of 0.6 could be constrained to \( \sigma_h \). This numerical simulation is used to discuss how faulting in the Zhengzhuang area affects the stress state.

4. Results and discussion

4.1. In situ stress and lateral pressure coefficient

The in situ stress data (Table 3) of 21 CBM well tests conducted in the No. 3 coal seam were mainly obtained from the Zhengzhuang area in the SQB. The in situ stresses and pore pressure versus depth are plotted in Fig. 6.

4.1.1. Formation pore pressure variation with burial depth

The Pearson’s correlation coefficient (r) for the formation pore pressure versus burial depth is 0.920, and the relation is as follows:

\[
P_o = 0.0091D - 0.448
\]

\( P_o \) increases linearly as the burial depth (D) of the coal seam increases. The \( P_o \) in partitions A, B and C versus permeability and porosity are displayed in Fig. 7. In partition A, which is mainly in normal compaction and has a relatively low elevation, there is an obvious trend.

Fig. 8. \( \sigma_h \) in partitions A, B and C versus permeability and porosity.
where the porosity gradually decreases with increasing $P_o$. The permeability in partition A also presents a similar trend, and the permeability is mainly in the range of 0.160–0.013 mD. In partition B, which is mainly under compaction and has a high elevation, the porosity mainly stays at approximately 4.1% when $P_o$ has small values. In partition A, the permeability has a clearly decreasing trend with increasing $P_o$, while the permeability in partition B mainly varies from 0 to 0.05 mD. The data in Fig. 7f indicate a reversed trend compared with the trends in partitions A and B. In partition C, which is mainly over compaction and has a relatively normal elevation, the porosity and permeability both increase with increasing $P_o$. Obviously, the distribution characteristics of porosity and permeability show clear differences among partitions A, B and C.

4.1.2. In situ stress variation with depth

The Pearson’s correlation coefficient ($r$) for $\sigma_H$ versus burial depth ($D$) is 0.784. The equation can be written as follows:

$$\sigma_H = 0.0294D + 5.5279$$ (15)

The Pearson’s correlation coefficient ($r$) for $\sigma_h$ versus burial depth is 0.845. The relationship between $\sigma_h$ and $D$ is fitted as follows:

$$\sigma_h = 0.0189D + 2.1776$$ (16)

Figs. 8 and 9 display $\sigma_H$ and $\sigma_h$ versus permeability and porosity in partitions A, B and C. The porosity decreases with increasing $\sigma_H$ in partitions A and C, while the value remains at approximately 0.02 mD in partition B. The $\sigma_h$ versus permeability and porosity is the same as that of $\sigma_H$ (Fig. 9). The results demonstrate that the porosity distribution is independent of the partition criteria in the Zhengzhuang area and that the permeability has specific characteristics for different partitions.

![Fig. 9. $\sigma_H$ in partitions A, B and C versus permeability and porosity.](image)

![Fig. 10. Lateral pressure coefficient versus permeability and burial depth of the coal seam.](image)
versus permeability (a); \( \xi_h \) versus permeability (b); \( \phi_H \) versus permeability and \( \phi_h \) versus permeability (c, d).

4.1.3. Lateral pressure coefficient

The lateral pressure coefficient (\( \kappa \)) is a crucial parameter for in situ stress, generally obtained by \( (\sigma_H + \sigma_h)/2\sigma_v \), which reflects the relation among \( \sigma_H, \sigma_h \), and \( \sigma_v \). Hoek and Brown (1980). The relation between \( \kappa \) and permeability can reveal the influence of \( \kappa \) on the fluid flow in coal reservoirs. The data were collected and analyzed by Meng et al. (2011) showed that \( \kappa \) are almost lower than 1.0 in the SQB. The extensional basin normally has more natural fractures and higher permeability than those in a compressional basin. As Fig. 10 shows, \( \kappa \) range generally from 0.86 to 1.79 with an average value of 1.20 in Zhengzhuang area, and \( \kappa \) can be classified as group I with \( \kappa < 1.0 \) and group II with \( \kappa > 1.0 \). For \( \kappa \) ranging between 0.8 and 1.0, the average horizontal stress is less than the overburden stress, and the permeability shows an opposite trend to the increase in \( \kappa \). Obviously, the area with \( \kappa < 1.0 \) is in extensional state has a relatively high permeability. For the other group II, \( 1.0 < \kappa < 2.0 \), which is in shallow formation, the permeability is mostly lower than 0.1 mD and remains at approximately 0.05 mD for an increasing \( \kappa \). Hoek and Brown (1980) and Hudson and Harrison (1997) showed that the shallowness formations are mainly in compressional basin or strike-slip and thrust faulting regimes. In contrast with the results calculated by Meng et al. (2011), the area with low permeability for group II with \( \kappa > 1.0 \) may present in compressional state considering the Zhengzhuang area is in normal faulting stress regime. Therefore, the \( \kappa \) value can be used to evaluate the high permeability zone.

4.2. Tectonic stress coefficient and the relative stress factor

The maximum/minimum horizontal tectonic stress coefficients (\( \xi_H, \xi_h \)) in the Zhengzhuang area were calculated using Eqs. (9) and (10). Fig. 11a and b show that the permeability has an opposite trend with increasing \( \xi_H \) and \( \xi_h \). The value of \( \xi_H \) is much higher than \( \xi_h \); thus, the \( \xi_H \) is the main manifestation of horizontal tectonic stress. The maximum/minimum horizontal relative stress factors (\( \phi_H, \phi_h \)) are calculated with Eqs. (12) and (13). Fig. 11c and d show that the permeability has a negative relationship with \( \phi_H \) and \( \phi_h \). Therefore, the lower horizontal tectonic stress coefficients and relative stress factors may indicate a high permeability zone in the Zhengzhuang area.

4.3. In situ stress direction

With the HF microseismic monitoring data, rose diagrams were mapped as the direction indicator of the fractures in the coal seam. Hubbert and Willis (1957) demonstrated that fractures generally propagate along the direction of \( \sigma_H \). Hence, the main direction of \( \sigma_H \) should be consistent with the main fracture direction in the coal reservoir. A total of 47 hydraulic fractures and 311 in situ fractures were monitored from 15 wells. Thus, the rose diagrams of in situ fractures and hydraulic fractures were mapped (Fig. 12). Obviously, the advantageous direction for in situ fractures is approximately in accordance with the strike of the Sitou and Houchengya faults (Fig. 12a). In addition, the direction of in situ fractures emerges with multiple directions near the fault zone (Sitou and Houchengya faults). However, the other wells far from the fault zone present as a single direction for in situ fractures. The multi-direction development of in situ fractures may be related to the complex in situ stress distribution in the fault zone. The hydraulic fracture direction of 15 wells in Fig. 12b shows a similar trend as the trend of the in situ fractures. The multi-direction hydraulic fractures are significantly less in number than the in situ fractures, especially in the fault zone. The microseismic monitoring data of both in situ and hydraulic fractures are summarized in Fig. 13. The main direction of in situ fractures is 45°–49° (Fig. 13a), while the direction changes over a wide range for the hydraulic fractures (40°–44°) in the Zhengzhuang area (Fig. 13b). Therefore, combining the main directions of both in situ and hydraulic fractures, the direction of \( \sigma_H \) is in the range of 40°–49°, which is close to the strike of the faults.

4.4. Implications for the petrophysical properties of the CBM reservoir

The shear stresses are displayed for the area near the faults in Fig. 14. The magnitudes and directions of the principal stress for horizontal layers are illustrated in Fig. 15. Fig. 15a and b indicate the maximum principal stress (\( \sigma_{max} \)) and the minimum principal stress (\( \sigma_{min} \)) for faulted horizontal sediments, respectively. The principal stress directions in the horizontal coal seam, roof and floor layers are illustrated in Fig. 15c and d. The magnitudes of shear stresses \( \sigma_{XY}, \sigma_{YZ} \) and \( \sigma_{ZX} \) vary from 15 MPa to 110 MPa, 35 MPa–170 MPa and 10 MPa–100 MPa, respectively (Fig. 14). The \( \sigma_{max} \) and \( \sigma_{min} \) vary from...
34 MPa to 200 MPa and 10 MPa–170 MPa. The directions of principal stresses are illustrated in Fig. 15c and d for horizontal faulted layers. Shear stresses (σ_{XY}, σ_{YZ} and σ_{ZX}) and principal stresses (σ_{max} and σ_{min}) are different from other layers in the fault zone, mainly due to the presence of two normal faults. Especially around the fault plane, the stresses are prominent and high. The high stress concentration implies that the coal seam underwent significant change. The current gas content of the No. 3 coal seam (Wang et al., 2016a, b) shows very low...
gas contents near the Sitou fault, which indicates that the faults hinder the sealing ability of the coal reservoir in the Zhengzhuang area. Clearly, the direction of the stress vector is intensive near the faults, and the orientation changes in the fault zone lead to a complex in situ stress state (Fig. 15d). The orientation in the fault zone is mainly SW-NE 45°, while the orientation becomes SW-NE 30° at the regional scale.

The porosity and permeability of the Zhengzhuang coal reservoir vary from 3% to 7% and 0.01 mD to 0.43 mD, respectively (Table 3). For the low permeability zone, HF is an indispensable way to enhance permeability by producing new fractures in the targeted seam (Hossain et al., 2000; Gale et al., 2007; Zhang and Chen, 2010; Majdi et al., 2012). The observed direction of \( \sigma_H \) and stress value could aid in well stimulation (Chatterjee, 2008). Because the fault greatly influences the orientation of \( \sigma_H \), evaluating the properties of faults and predicting the direction and magnitude of \( \sigma_H \) are crucial. This simulation provides an optional method that can be used to evaluate the reservoir permeability and optimize HF, especially for an area without adequate well test data. Therefore, this study may have significant implications for the petrophysical property evaluations of CBM reservoirs, which are favourable for CBM production.

5. Conclusions

In situ stress distribution and its influence on the CBM reservoir in the Zhengzhuang area of the SQB, North China were discussed in this study based on well testing, micro seismic fracture monitoring and numerical simulation. The tectonic stress coefficient, relative stress factor and lateral pressure coefficient were introduced to evaluate the reservoir permeability. A 3D numerical simulation was established to discuss the effects of faulting on the in situ stress state. The results may have significant implications for optimizing HF. The following conclusions were obtained:

1) The pore pressure and horizontal principal stresses (\( \sigma_H \) and \( \sigma_R \)) have a clear linear relationship with the burial depth of the coal seam. This well-correlated relationship should be useful for predicting the stress distribution of the area with few well test data in the research area.

2) \( \kappa \) can be classified into two groups in the Zhengzhuang area: \( \kappa < 1.0 \) and \( \kappa > 1.0 \). A lower \( \kappa \) indicates a higher permeability within an extensional basin. Thus, the \( \kappa \) value can be adopted to predict the high permeability zone. Moreover, the lower horizontal tectonic stress coefficient and relative stress factor are significant indicators of the high permeability area.

3) The direction of horizontal stresses can be effectively predicted with microseismic fracture monitoring data. Comparing microseismic fracture monitoring data with the simulation results, the horizontal principal stress direction obviously changes near the fault zone, suggesting that a complex in situ stress state exists, which is confirmed by the variation of the simulated stress field near the fault plane.
Fig. 15. The principal stresses: a) maximum principal stress. b) minimum principal stress. c) stress vector plot for the normal faulted coal seam, and d) stress vector plot in the rectangle as indicated in Fig. 15c for 3D normal faulted coal seam.

Acknowledgements

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Nomenclature

DTC the depth of the target coal seam, m
DTS shear wave slowness, s/m
E Young’s modulus, GPa
K coalbed permeability, mD
Pp formation pore pressure, MPa
Pp0 equal to the hydrostatic pressure, MPa
Pp1 shut-in pressure, MPa
Pp2 reopening pressure, MPa
R Pearson’s correlation coefficient
T tensile strength, MPa

Greek

ρ0 the density of the overlying strata, g/cm³
ρ1 the density of water, g/cm³
μ Poisson’s ratio
φ porosity, fraction
κ lateral stress coefficient, fraction
α Biot effective stress coefficient
ε relative compaction rate, fraction
εm maximum horizontal tectonic stress coefficient, fraction
εh the relative stress factor, fraction
φm the maximum horizontal stress factor, fraction
φh the minimum horizontal relative stress factor, fraction
σv overburden stress, MPa
σh maximum horizontal principal stress, MPa
σp minimum horizontal principal stress, MPa
σmax the maximum principal stress, MPa
σmin the minimum principal stress, MPa
σXY Shear stress in XY plane, MPa
σYZ Shear stress in YZ plane, MPa
σZX Shear stress in ZX plane, MPa

References


