Three-dimensional in-situ stress modeling of heterogeneous reservoirs with local faults

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Abstract. The Luzhou block in the Sichuan Basin has a smooth overall stratum, slight dip angle, and few fractures. Still, anticlines, folds, and faults are locally developed, and the distribution of in-situ stress is complicated. Since the in-situ stress field significantly influences on-site fracturing design, it is imperative to grasp the regional in-situ stress field's distribution law. The finite element method was employed to model the in-situ stress of the shale gas reservoir in the Luzhou block. The locally embedded fault network method was used to construct the primary faults in the formation. The information of in situ stresses in whole the geometric model and main shale gas reservoir layers, and on the fault surfaces can be acquired. The in-situ stress information of this area and a single local area was predicted, including stress gradients and stress disturbance range. The changes in the in-situ stress field are limited to the vicinity of the stress disturbance zone, and the changes in the formation stress far away from the fault are not apparent. The vertical stress of the Longmaxi formation is greatly influenced by the stress disturbance zone near the fault.

1. Introduction
In-situ stress measurement and evaluation technology can effectively guide the fracturing design, development plan, and other on-site work, which is of great significance to the development of oil and natural gas. In recent years, many in-situ stress measurement methods are commonly used in laboratories and on-site, including acoustic emission method and hydraulic fracturing method. However, the above methods still have limitations, such as actual complex operation, shallow effective measurement distance, and many factors that affect measurement accuracy. Numerical simulation methods have the advantages of high computational efficiency and low cost; they were quickly promoted and have been successfully applied to many fields of geology.

In recent years, numerical simulation of in-situ stress in complex structural formations is the subject of considerable research globally. [1] described a method to enable the boundary conditions of numerical models to be calibrated to stress measurements that contain a variety of local influences, including topographic and mining-induced stresses. [2] used the finite element method to predict the in-situ stress field to predict the opening pressure and opening sequence of natural fractures in the reservoir. [3] used borehole image logging in the front of the Eastern Alps to reveal reliable in-situ stress indicators from 62 wells. [4] analyzed the direction and magnitude of the in-situ stress of the No. 4 structure in the Nanpu Sag based on borehole leakage and acoustic emission measurement data. The observed interlayer...
differences are characterized as five different types of in-situ stress profiles. [5] analyzed the characteristics of the in-situ stress field in the Linxing block based on the diffusion coefficient and the borehole fracture characteristics explained by imaging logging and found that the differential stress increases with depth. [6] related models among the stress, burial depth, and permeability in coal reservoir No. 3 in the Shanxi formation were built, and the relationships among the coal fractures, coal permeabilities, and distribution of the modern stress were analyzed. [7] reappraised the in-situ stress orientation for central and northern England based on new interpretations of high-resolution borehole imaging for stress indicators, including borehole breakouts and drilling-induced tensile fractures. [8] realized the numerical simulation of the modern three-dimensional tectonic stress field in the Hailar block by using the finite element constraint optimization algorithm based on the analysis of the geological characteristics and actual data of the Hailar block. [9] used boundary element method and discrete element method to carry out numerical analysis to evaluate the stress state of rock mass caused by the excavation of underground quarry.

In summary, there are many numerical simulation analysis methods for the in-situ stress field. Still, the in-situ stress distribution law study lacks effective methods for complex lithological reservoirs with developed local faults, diverse structures, and substantial heterogeneity. There are few studies on distribution description and it is still in the exploratory stage. In terms of numerical simulation of the in-situ stress field, the finite element method is currently one of the most widely used methods. This paper used the finite element method to establish a three-dimensional in-situ stress model of the area L-Y, including discontinuous and non-penetrating faults and clarifies the distribution of in-situ stress in the reservoir. According to the theory of tectonic mechanics, the formation's geological information and lithological information were used to estimate the main formation Curvature, principal strain and principal stress and calculated the direction of principal stress. Then analyzed the influencing factors of the in-situ stress, and compared them with the example well, verified the accuracy of the model, and lay the foundation for efficient development of the block.

2. Background and overview
The studied areas are located in Luzhou block, southern Sichuan Basin, Sichuan Province, southwest China (figure 1). The shale gas exploration in this block started in 2011; 26 shale gas evaluation wells have been completed. As of June 2019, 16 shale gas wells have been put into production in the Luzhou block. The regional structure is located in the low-steep structural belt in southern Sichuan. The surface is mostly hilly terrain, the terrain is gentle, the average ground elevation is 300m~750m, and low mountains and steep hills dominate the landform. The faults are relatively developed, the middle and deep structures change greatly, and the folds are severe.

According to the three-dimensional seismic coverage, two parts in Area L-Y (Sub-areas L-3 and Y-1) and itself were selected for a trial numerical simulation. The main shale gas reservoir in this study is the Longmaxi formation. The stratigraphic lithology is dominated by shale; the average stratum thickness of Long-1 Formation is 67.2m.

![Figure 1. Studied areas in Luzhou regions.](image)

The rock mechanics properties, logging curve records, stratification data and other information of the reservoir are shown in figure 1. The Longmaxi gas shale formation is primarily formed of interlayered shale with dark gray siltstone, gray-green argillaceous shale and black carbonaceous shale.
With the decrease of stratum depth, the Longmaxi Formation consists of Long1 to Long2 sections. From bottom to top, Long1 Section contains Long1$^1$ to Long1$^4$ subsections (figure 2).

Figure 2. Typical stratigraphy of the study well area.

The fault information in Luzhou region is shown in figure 3. The shallow structure in the area is relatively gentle, the folds are simple, and the faults are not developed. As the depth increases, the stratigraphic structure becomes more complex, and the faults increase layer by layer, the strikes are multi-directional mainly N-E and E-W faults. Large-scale faults in the area are developed on the two wings of the main structure, which controls the structure. The fault direction on the plane is the same as the structural axis.

3. Method and equation

3.1. Method and procedure

Firstly, import the geological model of Petrel that contains the plane and sum into SolidWorks to improve the modeling accuracy. Then the geometric model in SolidWorks was converted into a file format that can be recognized by ABAQUS [10]. Secondly, the rock mechanics parameters and logging data obtained from the indoor test were screened and optimized, then expressed as a spatial coordinate function to reflect the geotechnical materials the inhomogeneity of shale reservoirs. Generated the three-dimensional zero-thickness discontinuous rectangular fault network based on geological data, set the stress displacement boundary conditions, use the least square method to continuously optimize the modeling solution, and finally obtain the in-situ stress field distribution results in line with the actual shale reservoir geological structure. The rock mechanical parameters used in this method were from indoor experimental results and oil field data.

Figure 4. Flow chart of modeling procedures of in-situ stress.

3.2. The locally embedded fault network method

The positioning elements of the fault usually include the fault position, the length of the fault, the inclination and the dip angle, etc. To make the model calculation efficient and easy to converge, in this paper, the discontinuous non-penetrating fault is regarded as a three-dimensional discontinuous rectangular plane with zero thickness, and the position of the fault and the fault group is uniquely determined by the coordinates of the four spatial vertices of the matrix (see figure 5). In the process of ABAQUS modeling, firstly, cut a common non-penetration surface in the geological body by cutting,
then insert a seam on the non-penetration surface to define the two surfaces of the fault by the grid.

4. Analysis of three-dimensional stress field constitutive model

In this paper, the area that will be studied is extensive, and there possibly exists the sliding internal friction in these local faults. On a geological scale, the strain induced by tectonic movement is minimal, so it is reasonable to consider that geomaterial only undergoes elastic deformation. Therefore, for less calculation and lower difficulty, it is suggested that the elastic constitutive is used. The linear elastic model based on the Hooke's law will be used in the remainder.

The displacement function is defined as a linear function about the node coordinates as the corresponding basis function to simplify the calculation difficulty, and its form is:

\[
\begin{bmatrix}
    u \\
    v \\
    w
\end{bmatrix} =
\begin{bmatrix}
    N_i & 0 & 0 & \cdots & N_i & 0 & 0 \\
    0 & N_i & 0 & \cdots & 0 & N_i & 0 \\
    0 & 0 & N_i & \cdots & 0 & N_i
\end{bmatrix}\begin{bmatrix}
    u_i \\
    v_i \\
    w_i
\end{bmatrix}
\]

Where \( N_i = N_i(x,y,z) \), \( i = 1, 2, \ldots, 8 \), \( u, v \) and \( w \) are the displacement functions of the node coordinates respectively.

According to the nature of the basis function, substituting the nodal coordinates of the element into it, the specific expression of the basis function can be solved, which is a linear function related to the nodal coordinates. Based on the above, the relationship between strain and nodal displacement matrix can be obtained according to the aforementioned Eq.(1), which can be expressed in a simplified matrix form as:

\[
\varepsilon = B\delta
\]

Where \( \delta=[u_i \ v_i \ w_i \ \cdots \ u_8 \ v_8 \ w_8]^T \) is the nodal displacement matrix; \( B \) is the geometric matrix, which is the matrix related to the basis function coefficients. Based on the above, according to the virtual displacement theory, the stiffness matrix and equation of the element can be obtained, which can be expressed in the following form:

\[
K\delta = F
\]

Where \( K \) is the stiffness matrix of a unit, \( F \) is the external force load matrix. Specifically:

\[
F = \begin{bmatrix}
    F_{1x} & F_{1x} & F_{1x} & \cdots & F_{1x} & F_{1x} & F_{1x} \\
    \end{bmatrix}^T
\]

\[
K_{lm} = V\mathbf{B}_l^T\mathbf{D}\mathbf{B}_m \] (l, m=1, 2, \ldots, 8); (4)

In Eq.(4), \( V \) is the unit volume, \( \mathbf{D} \) is the elastic matrix.

Based on the preceding, the stiffness matrix and equation of the element have been obtained. It is necessary to obtain the overall stiffness equation, and then the overall stress field and strain field can be calculated.

The superposition operation of the element stiffness matrix is required to obtain the overall stiffness matrix [11]. At this point, the corresponding element node displacement value can be obtained according to the known load situation. Then the element displacement function can be obtained according to Eq.(1), and then the stress field and strain field can be calculated.
5. Case Study

In this section, three cases (Areas L-Y, L-3 and Y-1) were conducted. After simulation accuracy and computational efficiency of the model were taken into consideration, the overall dimensions of the model are 40km in the W–E direction, 34km in the N–S direction and 6km in the vertical direction. The model was divided into 289,117 nodes and 179,052 elements.

5.1. In situ stress magnitude

Area L-Y is located in the Luzhou region. There is one well in area L-Y, two and three wells in area L-3 and Y-1, respectively. These test results through these wells can be used to validate the simulation accuracy. The calculation results of the in-situ stress in the L-Y well areas are as follows. It is found that the maximum horizontal in-situ stress in the formation below 3000m has increased significantly. The magnitudes of $S_{H_{\text{max}}}$, $S_{h_{\text{min}}}$, and $S_v$ were mainly between 93~117MPa, 85~98MPa, 88~114MPa, respectively, the stress gradient of $S_{H_{\text{max}}}$ was 2.7MPa/100m at 3835m, which is close to the actual measured value of a single well, which is in line with the expected result.

In ABAQUS, the path AB connected by the two points is selected. After measurement and conversion, the stress perturbation of the fault to the nearby stratum mainly occurs in the direction of $S_{h_{\text{min}}}$, and the influence range is 3~4.2km. The stress concentration near the fault is more evident in $S_v$, and the maximum change can reach 12MPa.

The degree of deflection in stress orientation was related to the attribute parameters of the fault, which included its scale (mainly the fault's slip), strike, filling material, and morphology. [12] propose that if the elastic modulus of the filling materials within a fault is lower than that of the surrounding rocks, the stress orientation will be deflected along the fault's strike; if the elastic modulus is higher, the stress orientation will be deflected perpendicular to the fault's strike; and if the elastic modulus of both are similar, there will be no deflection. The angle between fault strike and regional principal stress was the main factor that caused deflections in the in-situ stress field in the Longmaxi formation of area L-Y.

![Figure 6. Distributions of $S_{H_{\text{max}}}$, $S_{h_{\text{min}}}$ and $S_v$ in the L-Y area.](image)

![Figure 7. Stress distributions near the fault.](image)

Area L-3 is located in the Luzhou region(see figure 8). There are mainly two wells, Well #1, #2 as well as several cluster wells. Figure 2 shows distributions of $S_{H_{\text{max}}}$, $S_{h_{\text{min}}}$ and $S_v$ in typical reservoirs (Long1 formation), respectively. The magnitudes of $S_{H_{\text{max}}}$, $S_{h_{\text{min}}}$ and $S_v$ are 107.5, 89.3 and 97.8MPa at 3818m, respectively. The gradients of $S_{H_{\text{max}}}$ and $S_v$ are relatively close, and the horizontal stress difference in the reservoir is 15~20 MPa. The orientation of $S_{H_{\text{max}}}$ is almost N90~110° E.

![Figure 8. Distributions of $S_{H_{\text{max}}}$ on the fault surface in the L-3 area.](image)

![Figure 9. Distributions of $S_{H_{\text{max}}}$ in the Y-1 area.](image)
The characteristics of in-situ stress in the area where the fault is developed are closely related to the spatial location. The top of the fault has a higher stress value, and the area near the end of the fault is a relatively low-stress value area, and the stress concentration is evident near the middle.

The Y-1 area's stress field simulation results indicated that for the distribution of $S_{H\text{max}}$ magnitude (see figure 9), The magnitude of the in-situ stress has an uneven increase near the Wufeng formation. This was consistent with the trend observed in the measured data. The range of the $S_{H\text{max}}$ magnitudes was mostly 99–112MPa. The average stress gradient was 2.48MPa/100m. Where the fault scale was large, it resulted in an enormous range in low-magnitude zones.

The distribution trend of $S_{h\text{min}}$ magnitude was similar to that of $S_{H\text{max}}$, that is, lower in the central part and fault zone and higher in the surrounding area. The magnitudes were mainly between 84–98MPa and the average stress gradient was 2.34MPa/100m. For $S_{V}$, the magnitudes were about 92–105MPa, and the average stress gradient was 2.55MPa/100m. Overall, horizontal differential stress did not exceed 26MPa and was generally below 15MPa.

According to the prediction results, drew the maximum horizontal principal stress distribution maps at different depths. As shown in figure 10, the horizontal all-directional in-situ stress values gradually increase as the depth increases. The correlation between the $S_{H\text{max}}$ distribution and the depth reaches 0.89, and the correlation is well.

5.2. In-situ stress orientations
The direction of the maximum horizontal principal stress in the east-west region is N122°E. Affected by the pre-existing fault, when the stress acts on the fault, it will generate a component force along the direction of the fault, making the direction of $S_{H\text{max}}$ occur eastward for deflection, the maximum horizontal principal stress direction difference between the east and west sides is about 15°. The influence range of the stress direction of the southwest-north-east faults in the study area is slightly smaller than that of the southeast-northwest faults, such as the northwestern fault. When the tectonic stress is conducted in the fault area of different strikes, the changes of effective physical parameters lead to changes in the magnitude and direction of the ground stress near the fault.

5.3. Model validation
Compare the six sets of prediction results of the three areas (L-Y, L-3 and Y-1) with the actual test results, as shown in Table 1. It can be seen that the forecast errors are all less than 10%, which is within the engineering allowable error.

| Well number | Depth(m) | $S_{H\text{max}}$, MPa | $S_{h\text{min}}$, MPa | $S_{V}$, MPa |
|-------------|----------|------------------------|------------------------|-------------|
|             | Modeling | Test                   | Error(%)               | Modeling    | Test       | Error(%)   |
| #1,L-Y      | 3835     | 102.8                  | 109.7                  | 6.7         | 86.4       | 94.3       | 9.1         | 93.4     | 97.9       | 6.7       |
| #1,L-3      | 3818     | 107.5                  | 109.6                  | 2.0         | 89.3       | 93.5       | 4.7         | 97.8     | 101.3      | 3.6       |
| #2,L-3      | 3620     | 106.9                  | 101.1                  | 5.7         | 90.3       | 87.2       | 3.6         | 96.1     | 94.4       | 1.8       |
| #1,Y-1      | 3785     | 105.4                  | 97.9                   | 7.7         | 93.1       | 87.3       | 6.6         | 97.6     | 90.1       | 8.3       |
| #2,Y-1      | 4123     | 113.4                  | 111.7                  | 1.6         | 92.3       | 96.8       | 4.9         | 100.6    | 102.6      | 2.0       |
| #3,Y-1      | 4147     | 118.3                  | 115.2                  | 2.7         | 95.7       | 99.1       | 3.6         | 103.4    | 105.3      | 1.8       |
6. Conclusion
In this study, the finite element numerical simulation method combined with local fault network modeling was used to determine the orientation and magnitude of in-situ stress in Luzhou region. Our approach of applying a combined modeling technique using Petrel and ABAQUS fully tapped the advantages of both software packages and facilitated the construction of 3D models. These improved the accuracy of simulated results, especially in terms of the clear presentation of inter-strata in-situ stress characteristics. The following conclusions were made:

1) The overall construction of a three-dimensional in-situ stress model can more truly reflect the in-situ stress distribution of the research area. In contrast, the modeling of a local single well area can accurately predict the state of stress changes near the fault.

2) The shale reservoir in the Luzhou block in the Sichuan Basin has a high degree of stress concentration; the $S_{\text{Hmax}}$ of the Longmaxi formation is generally above 105MPa. Overall, horizontal differential stress did not exceed 33MPa and was generally below 18MPa. The direction of the $S_{\text{Hmax}}$ is generally near N120° E.

3) The changes in the in-situ stress field are limited to the vicinity of the stress disturbance zone, and the changes in the formation stress far away from the fault are not apparent. The fault has the greatest influence on the horizontal maximum principal stress, and a stress disturbance zone will be formed near the fault, and the influence range is 3~4.2km. The vertical stress of the Longmaxi formation is greatly affected by it.

7. Future works
At present, the plastic deformation and creep behavior of shale has become a hot spot for studying rock mechanics of deep shale reservoirs. In the next step, it is necessary to upgrade the constitutive model from a simple linear elastic model to a more realistic plastic model. And in the calculation process of the in-situ stress field, the more detailed the description of the three-dimensional complex geological body, the higher the prediction accuracy of the in-situ stress field. Therefore, if more detailed fault information can be obtained, the next step can be to extend the description of the fault from the 3D plane to the 3D surface.

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