The constraint of deep rock stresses in H underground gas storage based on a modified stress polygon and focal mechanism solution

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Abstract. H underground gas storage (H-UGS), located in the junction of the southern margin of the Junggar Basin and the eastern part of the northern Tianshan Mountains, is one of the large natural gas storage in China. It is of significance to study the deep rock stresses in H-UGS for fault slip tendency, safe storage of energy and other research. Most of the regional stress information in H-UGS data from in-suit measurements lacks deep in-suit stress data in this region. This research proposes a hybrid constrain stress magnitudes present in deep rock masses. First, the fault friction strength, an essential parameter of lateral pressure coefficient polygon, is established by the stress accumulation index method and apparent friction strength evaluation method. Second, we inverse the stress factor R from the focal mechanism solutions in this area, and the lateral pressure coefficient polygon is qualified quadratic to narrow down the range of results by this parameter. Finally, the complete stress profile of H-UGS is obtained by using the simple transition relationship between lateral pressure coefficient and in-situ stress. The result shows that the principal compressive stress of the H-UGS region is determined by the N22°E, the maximum lateral pressure coefficient Kₘₐₓ (or S_h) at three depths (3.0km, 6.5km, and 12.0km) are 1.2 (80.22 MPa), 1.22 (202.72 MPa), 1.28 (421.34 MPa) respectively, and the minimum lateral pressure coefficient Kₘᵋₙₜ (or S_i) are 0.87 (58.21 MPa), 0.86 (142.12 MPa), 0.86 (282.61 MPa) respectively. The result is primarily consistent with in-situ measurement from the depth of 3.0km to 3.7km. The maximum horizontal principal stress and the minimum coincidence ratio are 54% and 69%. The result of estimating deep rock stresses established in this research provides sufficient regional stress field data in H-UGS.

1. Introduction
H-UGS is located at the junction of the southern margin of the Junggar Basin and the eastern part of the northern Tianshan Mountains. The deformation characteristics reflect the coupling between the Tianshan and the Junggar Basin. Historically, it experienced the structural deformation of the Yanshanian and Himalayan periods, and current regional tectonic deformation is mainly related to the Himalayan tectonic movement. The magnitude and direction of in-situ stress change with time and space. There is a lack of complete stress profile, mainly short of deep in-situ stress data in the study area. Therefore, determining the characteristics of the in-situ stress field in the deep is essential for designing and evaluating gas storage.
There are more than 10 widely accepted in situ stress measurement and estimation methods, most of which acquire stress data from the shallow crust. Take hydraulic fracturing methods as an example, the maximum test depth is 9.1 km, and the usual test depth is up to 1 km \cite{1}. These data have provided support for preventing disasters during shallow soil and rock engineering. Currently, resource mining already goes further beyond the 1 km limit. For example, the depth of oil and gas production reaches 7.5 km. Generally, empirical estimate and theoretical prediction are utilized to define stress state in deep rock masses quantitatively. The primarily former relies on empirical fitting formulas. In earlier years, Hoek and Brown \cite{2} presented a stress estimation equation based on the ratio K of principal horizontal stress to vertical stress (K = 0.3–0.5), Li et al \cite{3} yielded the distribution of lateral pressure coefficients as a function of burial depth and the depth-specific linear calculation formula for principal horizontal stresses by fitting in-suit stress measurements. In the present study, a lateral pressure coefficient polygon is acquired by improving the stress polygon. Then, the lateral pressure coefficient is constrained for a second time according to the particular type of fault stresses using both the shape ratio R and the frictional strength-based in-situ stress constraining method to provide a more accurate prediction of deep in-situ stresses.

In our study, this method is applied to define the deep in-situ stresses of H-UGS. The result shows that the principal compressive stress of the H-UGS region is N22°E, the maximum lateral pressure coefficient Kmax (or SH) at three depths (3.0km, 6.5km, and 12.0km ) are 1.2 (80.22 MPa), 1.22 (202.72 MPa), 1.28 (421.34 MPa) respectively. The minimum lateral pressure coefficient Kmin (or Sh) are 0.87 (58.21 MPa), 0.86 (142.12 MPa), 0.86 (282.61 MPa) respectively. The result is most consistent with in-situ measurement from the depth of 3.0km to 3.7km. The maximum horizontal principal stress and the minimum coincidence ratio are 54% and 69%. The result of estimating deep rock stresses established in this research provides sufficient regional stress field data in H-UGS.

2. Regional geological information of study area

The H-UGS is located at the southern margin of the Junggar Basin and the eastern part of the northern Tianshan Mountains, which is the junction of the Junggar Basin and the Tianshan Mountains. As shown in Figure 1, the H-UGS is 5 km from west of Hutubi County and 78 km southeast of Urumqi City, regional deformation characteristics of the H-UGS reservoir area reflect the tectonic coupling between the North Tianshan and Junggar Basin. Since the Carboniferous, southern margin of the Junggar Basin has experienced Carboniferous-Early Permian rifts, limited ocean basins and foreland basin evolution, Middle Permian-Jurassic period intracontinental depression, Cretaceous-Late Quaternary period foreland basin evolution in three development stages\cite{4}. The continental integration was completed in the Late Carboniferous-Permian, and the Mesozoic entered the stage of intracontinental evolution. The structural deformation was mainly related to a series of collision events in the Tethys tectonic domain \cite{5}. The structural deformation of the present work area is mainly related to the Himalayan tectonic movement. It has the characteristics of north-south zoning, east-west segmentation, and upper and lower stratification. From the sedimentary data of the basin, the thick coal seams developed in the Jurassic and the gypsum shale layers developed in the western part of the Neogene, these soft layers with higher plasticity play an essential role in the deformation. Under this complex geological structure condition, the magnitude and direction of the stress field change with time and spatial location\cite{6}, so the characteristics of the in-situ stress field will be an essential parameter for evaluating the design and operation of natural gas storage.
The gas reservoir is the Ziniquanzi Formation, and the overlying is the mudstone caprock of the Anji Haihe Formation. It is about 838 m thick and is stably distributed throughout the area. The underlying is the Donggou Formation. Integrate contact relationships. The anticline is located at the east end of the third row of structural belts in the North Tianshan Piedmont Depression. The overall three-dimensional structure is a long-axis fault anticline with a nearly east-west distribution cut by the Hutubi fault. The east-west length is about 12.8 km and the north-south width is about 7.8 km. There are mainly three reverse faults dipping from east to west to the south in the Ziniquanzi Formation. The dip angle of the section gradually increases from the bottom to the top. The upper fault section almost along with the Jurassic coal seam slippage [7].

3. Constraint deep rock stresses by modified stress polygons and R

3.1. A modified stress polygon

In light of Anderson’s theory and the Mohr-Coulomb criterion, Zoback et al.[8] constrained in situ stresses in the crust. Based on these theories, we can derive the relations of the maximum and minimum effective principal stresses versus frictional strength for a fault region without considering the cohesive force:

$$\frac{\sigma_1}{\sigma_3} = \frac{S_1 - P_p}{S_3 - P_p} \leq (\mu^2 + 1) + \mu$$  \hspace{1cm} (1)

Where $\sigma_1$ and $\sigma_3$ are the maximum and minimum effective principal stresses, respectively, $S_1$ and $S_3$ are the three principal stresses; $P_p$ is porewater pressure, and $\mu$ is the fault frictional coefficient. According to Anderson’s fault classification theory, Zoback et al.[8] introduced the concept of the stress polygon, as shown in Figure 1. Here, NF, SS, and RF respectively represent normal, strike-slip, and reverse faults.
When estimating stresses at different depths, in situ stress polygon approaches are very inconvenient (since more than one stress polygon must be drawn). According to the characteristics of a stress polygon, Wang et al.\cite{9} improve the corresponding relations among the principal stresses for the three basic fault types:

\[
\begin{align*}
    k_{\text{max}} & \leq (\sqrt{\mu^2 + 1} + \mu)^2 \text{(Reverse fault)} \\
    k_{\text{min}} & \leq (\sqrt{\mu^2 + 1} + \mu)^2 \text{(Strike-slip fault)} \\
    1/k_{\text{min}} & \leq (\sqrt{\mu^2 + 1} + \mu)^2 \text{(Normal fault)}
\end{align*}
\] (2)

Where \(k_{\text{max}}\) and \(k_{\text{min}}\) are the maximum and minimum lateral pressure coefficients for effective stresses, expressed as \(k_{\text{max}} = \sigma_1 / \sigma_v\) and \(k_{\text{min}} = \sigma_3 / \sigma_v\), and the other symbols are the same as defined above. According to equation (2), we can obtain a lateral pressure coefficient polygon using a stress polygon as a reference. Figure 2 shows that the lateral pressure coefficient polygon describes the relationship between the lateral pressure coefficient and the frictional coefficient. Hence, the stress trend determined by the lateral pressure coefficient can be obtained with only one polygon. In a hydrostatic context, the transformational relation between the lateral pressure coefficient for effective stresses and that for in situ stresses is expressed by equation (3):

\[
K_{\text{max,min}} = (1 - \gamma_w/\gamma_r) k_{\text{max,min}} + \gamma_w/\gamma_r
\] (3)

Where \(K_{\text{max}}\) and \(K_{\text{min}}\) are the maximum and minimum lateral pressure coefficients, respectively expressed as \(K_{\text{max}} = S_1/S_v\) and \(K_{\text{min}} = S_3/S_v\); \(\gamma_w\) and \(\gamma_r\) are the bulk density of pore water and the average bulk density of the overlying rock, respectively.

3.2. Constraining stresses using both R and modified stress polygons

Shape ratio \(R\) is an essential parameter in the inverted earthquake FMS that describes the relative level of the three principal stresses, as well as an important tool for investigating the interactions between earthquake focal mechanisms and the in-situ stress field. It is expressed as\cite{10}:

\[
R = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}
\] (4)
Where R is the stress form factor. As the three principal stresses cannot correspond to the maximum horizontal, minimum horizontal, and principal vertical stresses without knowing the fault state, Anderson’s theory is used as a basis to discuss the stresses under different fault states. According to equation (2), by introducing the corresponding relations among the principal stresses for a particular stress state into equation (5), we can obtain the functional expression between the principal horizontal stresses with R as the coefficient:

\[
\begin{align*}
\text{Normal fault:}\quad & \sigma_{H} = R\sigma_\alpha + (1-R)\sigma_\gamma \\
& k_{\text{max}} = R k_{\text{max}} + 1-R \\
\text{Reverse fault:}\quad & \sigma_{H} = \frac{1}{1-R}\sigma_\alpha + \frac{R}{R-1}\sigma_\gamma \\
& k_{\text{max}} = \frac{1}{1-R} k_{\text{max}} + \frac{R}{R-1} \\
\text{Strike-slip faults:}\quad & \sigma_{H} = \frac{R}{R-1}\sigma_\alpha + \frac{1}{1-R}\sigma_\gamma \\
& k_{\text{max}} = \frac{R}{R-1} k_{\text{max}} + \frac{1}{1-R}
\end{align*}
\]

As shown in Figure 3, the constraint lines of R for different fault stress states pass point (1, 1) and, when R is the extreme value 0 or 1, it coincides with the boundaries of the polygons for different fault states. It can verify that the stress form factor can constrain stresses for a second time following constraints by a stress polygon or a lateral pressure coefficient polygon.

![Figure 3. Constraint of deep rock stress based on a modified stress polygon and FMS](image)

3.3. Stress analysis of the H-UGS

3.3.1. Analysis of stress data from in-situ measurement

The data of 7 measured sites in the H-UGS gas reservoir zone by oil drilling test and the laboratory core test. Among the 3km data of Well Hu 2 comes from the core acoustic emission laboratory test data. The three-dimensional stress gradients are 0.027 MPa/m, 0.018 MPa/m, and 0.024 MPa/m respectively. The maximum horizontal principal stress direction is determined by hydraulic fracturing stimulation and borehole imaging of Well 001, Well Hu003, and HUK24. Li Minhe et al [11] determined the horizontal stress gradient of the late Tertiary of the H anticline to be 0.036 MPa/m and 0.023 MPa/m respectively. Through the statistics of multi-variety data, it is obtained that the overburden depth range is 10.8-2309 m, the maximum horizontal principal stress gradient is 0.029MPa/m, the minimum horizontal principal stress gradient is 0.021MPa/m; the buried depth
ranges from 2309 to 3047m, the principal stress gradient is 0.026 MPa/m, the minimum horizontal principal stress gradient is 0.017 MPa/m; From 3047m to 3622m (gas reservoir), the maximum horizontal principal stress gradient is 0.024 MPa/m, and the minimum horizontal principal stress gradient is 0.018 MPa/m. From 3622m to 4293m, the maximum horizontal principal stress gradient is 0.024 MPa/m, and the minimum horizontal principal stress gradient is 0.015 MPa/m. At the same time, according to the Fundamental database of crustal stress environment in continental China [12], the stress data near the study area (latitude 43°N~45°N, longitude 85°E~89°E), the maximum horizontal principal stress and minimum horizontal principal stress in the study area with depth as shown in Figure 4. According to shallow stress profile, stress accumulation index \(\mu_m\) can be calculated to evaluate the friction strength \(\mu\), which is about 0.4 in H-UGS area.

![Figure 4. The shallow stress profile and stress accumulation index in the study area](image)

3.3.2. Analysis of deep stress data from modified stress polygon

The Focal Mechanism Solution (FMS) is fundamental to investigating earthquake preparation environments, earthquake genesis, and deep structures. Small earthquake FMS has some advantages in estimating regional stresses. So we obtained the P, T, and B axes of earthquakes from FMS calculated along the initial motion direction of small earthquakes in the H-UGS area. Using the P, T, and B axes of FMS, we deduced the three principal stress axes of the tectonic stress field and the tectonic stress characteristics of the H-UGS area. The earthquake focal depth was 3–13 km; the magnitude was 2–4.8. Because the stresses for a particular depth or a particular depth range were to be determined, it was necessary to subdivide the resulting FMS for a second time to obtain the focal mechanism information for different depths or depth ranges. Using the small earthquake focal depth frequency histogram, as shown in Figure 5, the depths at which the frequency is higher than those of adjacent intervals were selected as characteristic depths to inverse the small earthquake FMS group-by-group. In this diagram, the characteristic depths of the study area are 6 km and 10 km, which is extended to 3–8 km and 9–13 km, intervals according to the actual numbers of foci at each depth interval for further inversion.
Figure 5. The shallow stress profile in the study area

We use the lateral pressure coefficient $K$ and the focal mechanism to solve the stress shape factor $R$ combined with the stress polygon theory to predict the deep stress. This method has high requirements for the accuracy of the principal vertical stress, a total of 57 focal mechanisms selected in the study area. The shape ratio $R$ of the FMS is calculated in two depths of 6km and 10km. The result shows that effective ranges of $R$ are 0.46~0.69 and 0.52~0.78, and deep formation density is queried from the global crustal model Crust1.0 (http://igppweb.ucsd.edu/~gabi/rem.html) and the queried range is latitude 43°N~45°N, longitude 85°E~89°E. All parameters we used and calculation results are shown in Table 1.

| Depth/m | $\rho$/(g/cm3) | $P_P$/Mpa | $S_H$/Mpa | $K_{min}$ | $K_{max}$ | $S_h$/MPa | $S_H$/MPa |
|---------|----------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 3000    | 2.37           | 31.5      | 66.85     | 0.87      | 1.2       | 58.21     | 80.22     |
| 3670    | 2.37           | 38.54     | 82.64     | 0.87      | 1.2       | 71.87     | 99.34     |
| 4530    | 2.54           | 47.58     | 115.09    | 0.86      | 1.22      | 98.6      | 140.64    |
| 6530    | 2.74           | 68.58     | 165.89    | 0.86      | 1.22      | 142.12    | 202.72    |
| 12000   | 2.74           | 126.01    | 328.83    | 0.86      | 1.28      | 282.61    | 421.34    |

3.3.3. Comprehensive analysis of stress profile

Complete regional stress field data include stress magnitude and direction. In this study, the stress direction depends on both small earthquake focal mechanism inversion and in-situ stress measurement. As shown in figure 6, the direction of the maximum horizontal principal stress measured in the far-field is north-south, and the borehole data of the 6 measured sites in the near-field is drawn in a rose diagram of the direction of the maximum horizontal principal stress, and the dominant direction of the maximum horizontal principal stress is N26°E. Based on the above multiple stress direction analysis methods, the measured results of the near and far-field are basically consistent with the approximate direction of the focal mechanism P axis. It can be comprehensively obtained that the direction of the modern initial in-situ stress field in the study area is N22°E.
According to the calculated data in Table 1 and the measured data distributed over 6km, the stress prediction profile of the study area is shown in Figure 6. It shows that the prediction profile gradually increases with the depth, and the stress state appears to be strike-slip type, which is consistent with the results of the measured stress state in the shallow part. While the predicted stress range appears stepped, the analysis of the reason mainly depends on the influence of the formation density, but from the perspective of the shallow prediction results, the stress prediction range based on density logging is in good agreement with the measured point value, that is, from From the depth of 3.0km to 3.7km, the coincidence ratios of the maximum horizontal principal stress and the minimum horizontal principal stress are 54% and 69%, respectively. The analysis should be the large influence of stress fluctuations in the reservoir section and adjacent formations. Of course, in the study of the in-situ stress field, the stress in the deep crust will not increase linearly from the shallow stress. The horizontal stress will be affected by complex geological conditions and the regional in-situ stress field. In contrast, the principal vertical stress mainly comes from gravity and the pressure of the overburden. After the depth reaches a specific value, it must be greater than the maximum horizontal principal stress value. Li Minhe et al. [11] studied the in-situ stress about 5km deep also fully proves this characteristic. It is comprehensively concluded that the deep stress prediction method has reasonable practicability, which is of great significance for the study of H-UGS regional stress characteristics, the study of deep reservoirs in gas storage, and even the study of shallow earthquakes in this area.

**Figure 6.** (a) Stress direction in far-filed; (b) Stress direction in near-filed; (c) Stress direction in inversion of FMS

**Figure 7.** Complete stress profile of H-UGS
4. Conclusions

(1) The statistical analysis of the maximum principal stress direction of the in-situ measurement shows that the maximum horizontal principal stress direction measured in the far-field is north-south, the maximum horizontal principal stress in the near-field is N26°E. The near-field measured results and the far-field measured results consist of the approximate direction of the focal mechanism P axis. Comprehensively, the direction of the modern initial in-situ stress field in the study area is N22°E.

(2) The maximum lateral pressure coefficient $K_{\text{max}}$ (or $SH$) H-UGS region at three depths (3.0km, 6.5km, and 12.0km) are 1.2 (80.22 MPa), 1.22 (202.72 MPa), 1.28 (421.34 MPa) respectively, and the minimum lateral pressure coefficient $K_{\text{min}}$ (or $Sh$) are 0.87 (58.21 MPa), 0.86 (142.12 MPa), 0.86 (282.61 MPa) respectively. The result is most consistent with in-situ measurement from the depth of 3.0km to 3.7km. The maximum horizontal principal stress and the minimum coincidence ratio are 54% and 69%.

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