Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 3934398, 10 pages
https://doi.org/10.1155/2022/3934398

Research Article

Distribution of In Situ Stress in Northwest Jiaodong Peninsula

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Received 17 December 2021; Revised 18 May 2022; Accepted 29 August 2022; Published 26 September 2022

Academic Editor: Qi Jia

In order to study the present state of the tectonic stress field in northwest Jiaodong Peninsula, the characteristics of the ground stress distribution along depth were analyzed with the method of regression analysis. A total of 164 items of in situ stress measurement data were collected. There are mainly two types of in situ stress states, one is $\sigma_{H}>\sigma_{h}>\sigma_{v}$ and the other is $\sigma_{>}\sigma_{v}>\sigma_{h}$, and the type of in situ stress state is related to the depth. The principal stresses σ_H, σ_h, and σ_v increase approximately linearly with depth, and the stress gradients are 0.0556, 0.0248, and 0.0346, respectively. The lateral pressure coefficients *K*H, *K*h, and *K*av vary approximately hyperbolically with the increase in depth and approach 1.99, 1.12, and 1.56, respectively. The ratio of half of the maximum horizontal differential stress to the average horizontal principal stress μ_{d} varies linearly with the increase of depth and approaches the value of 0.33. The maximum shear stress τ_{m} increases approximately linearly with depth, and the stress gradients are 0.0146. The ratio of horizontal principal stress difference with vertical stress on 1000 m–2000 m is 0.5– 0.7. In addition, the maximum level of principal stress advantage direction in the northwest Jiaodong Peninsula is nearly E–W.

1. Introduction

In situ stress is the natural stress existing in the crust undisturbed by engineering, also known as the initial stress of rock mass, absolute stress, or original rock stress. The in situ stress state is an important index to characterize engineering geological disasters, earthquake preparation, and mine safety construction. The study of in situ stress measurement and its distribution characteristics is a basic and very important work in the process of underground engineering construction. The measured data of in situ stress can not only directly reflect the characteristics of the regional in situ stress field but also help to explain the problems of fault activity, crustal movement, and the dynamic source of plate evolution. The northwest Jiaodong Peninsula is located in the easternmost part of Shandong Province, which is the third largest gold-producing region in the world. The complex geological structure of the area is not conducive to mining activities. Despite the particular importance of in situ stress measurement in this area, it is still vacant. The distribution law of regional in situ stress is the foundation for underground engineering construction. Scholars have carried out many studies on regional in situ stress. Sandiford et al., respectively, conducted in situ stress studies in Southeast Australia, Japan Island, South Africa, and the Qinshui Basin [1–4]. After the in situ stress measurement method was introduced in China, many earthquake-prone areas and resource-intensive areas have carried out a lot of work. Many scholars have also studied the local stress field characteristics in the Shandong area. Zheng [5] carried out in situ stress measurements near the coast of the southern Bohai Sea. Liu [6] measured the in situ stress of the sea working face of Beizao mine. Cai and Qiao measured gold mines such as Sanshandao [7, 8]. But in the Jiaodong Peninsula, especially in the northwest Jiaodong Peninsula where rare metal resources are enriched, the in situ stress characteristics are still blank. In order to fully grasp the distribution characteristics of the in situ stress field in the northwest Jiaodong Peninsula, the distribution characteristics of the in situ stress field in this area were analyzed based on the in situ stress measurement data of the author and others for many years. In particular, the data from the Sanshandao gold mine, Linglong gold mine, and Xincheng gold mine provide important support for this paper. The research results fill the gaps in the characteristics of in situ stress in the Jiaodong Peninsula and provide reliable data for mine engineering construction, tunnel construction, and the study of earthquake focal mechanisms in the area.

2. Geological Tectonic Environment in the Northwest of Jiaodong Peninsula

Shandong is located in the east of the north China block, in the Jiaodong Peninsula between the Bohai Sea and the Huanghai Sea, and is affected by the joint push of the Pacific plate and the Philippine plate. There were a long evolutionary history and complex geological tectonic environment in the area, including the stable ancient land block of the Archean, the Paleozoic Proterozoic activity zone, and the stable Paleozoic land surface sea deposition in Claratong [9]. The NNE-trending and NE-trending faults are the main faults in the northwestern Jiaodong Peninsula. NE-trending faults have the characteristics of right-lateral strike-slip and mainly exhibit compressive-torsional activities including the Yishu fault zone (NNE-trending) and the Zhaoping fault zone (NE-trending). Figure 1 shows the basic pattern of active fracture structures in Shandong Province, some of which are still active at the present stage [11, 12]. These faults have an obvious control effect on the regional formation, tectonic movement, magmatic activity, and mineral distribution.

The Shandong section of the Tanlu fault zone runs between western Shandong, Jiaodong plots, and the Sulu super high voltage metamorphic zone, the fracture zone extending about 360 km towards N(10°~25°)E. Affected by the Tanlu fault belt, the geological environment of the northwest Jiaodong Peninsula and the south Bohai Sea area is more complex. However, this area is an important mineral resource area in China, especially for rare and precious metals. The Jiaodong Peninsula is located at the intersection of mainland East Asia and the western Pacific plate. It is a tectonic shear belt related to the East Asian mainland and the western Pacific activity belt. It is controlled by the regional counterclockwise torsional stress field, forming an active region of the Neocathaysian system. The geotectonic is located in the Jiaodong uplift area of the second uplift zone of the giant tectonic zone of the Neocathaysian system, adjacent to the Tanlu fault zone in the west, the Bohai Bay Basin in the north, the Pacific plate in the east, and the Dabieshan-Sulu super high voltage metamorphic zone in the south [13, 14]. Multistage tectonic magmatic activity in the Jiaodong region has developed a crisscross complex tectonic network. The base structure in the area is a Qixia anticlinorium and fracture structure composed of Precambrian formation, and its tectonic line direction is near the EW direction. Controlled by the collision orogenic and subduction region structural stress field, the fracture structure system is dominated by NE and NNE to the fracture structure. There are 7 fault zones in the region, in turn from west to east, namely, Sanshandao-Cangshang fault, Xincheng-Jiaojia fault, Zhaoyuan-Pingdu fault, Qixia fault, Muping–Jimo fault, Jinniu Mountain fault, and Mishan fault. The first four are in the west of Jiaodong, and the overall trend is in the NE direction. The latter two are located in the eastern part of Jiaodong and generally move towards the near-SN direction. The Muping–Jimo fault is in the junction zone, which is a boundary fault and generally towards the NE direction [15].

3. Source and Cause of In Situ Stress in the Northwest of Jiaodong Peninsula

In situ stress is a general term for stress within the Earth, which is the distribution of in situ stress within a spatial range [16–20]. The formation of in situ stress is mainly related to various dynamic processes of the Earth. The geological activities in the northwest Jiaodong Peninsula are frequent and the geological conditions are very special, which makes the source of regional in situ stress more complicated. But long after in situ stress was proposed, it was widely believed to be only related to overburden weight. Until 1950s, Hast proposed that the in situ stress is not only the vertical stress formed by the overlying strata but also the horizontal stress caused by tectonic stress [21]. For the first time in the tunnel, we proposed that the horizontal stress is much greater than the vertical principal stress, and it was gradually recognized that the tectonic movement is a major factor in forming the in situ stress [22–24]. A number of studies have found that influenced by the collision and extrusion of the Indian plate and the Eurasian plate, the distribution of the maximum principal stress in China is obviously regular. Ma [25] according to the unity and stability of the principal stress direction and the relation of three principal stresses with depth, with the obvious turning area and the principal stress value or stress gradient as the boundary, the crust stress area is divided (Figure 2).

The northwest Jiaodong Peninsula is on the eastern coast of China. This region is a complex of geological records formed in important geological periods, which are preserved by ancient plots after multistage insertion, superimposition, and denudation, with a variety of structural combinations and styles [26–29]. The basic structural frame appears in the basin ridge, from north to south, Longkou Basin, Jiaobei uplift, and Jiaolai Basin. This structural pattern is the response to the Mesozoic mantle uplift and the lithosphere thinning in the crust. During the T3-K1 period, the region with a tectonic extrusion-extension effect was obvious [30], and the extrusion-extension model of the accordion structure in the Jiaodong area was formed.

After a large number of field investigations and experimental studies, the main tectonic activities of the Jiaodong Peninsula were divided into four periods. Stress characteristics are characterized by extrusion and extension interaction [31, 32]. The first period is mainly extrusion, which can be divided into two stages: NW-SE in the early stage and near S-N in the late stage. ① Early stage near NW-SE extrusion, forming the left-line translation fault in the NNE-SSW direction. ② Late stage near S-N extrusion, mainly

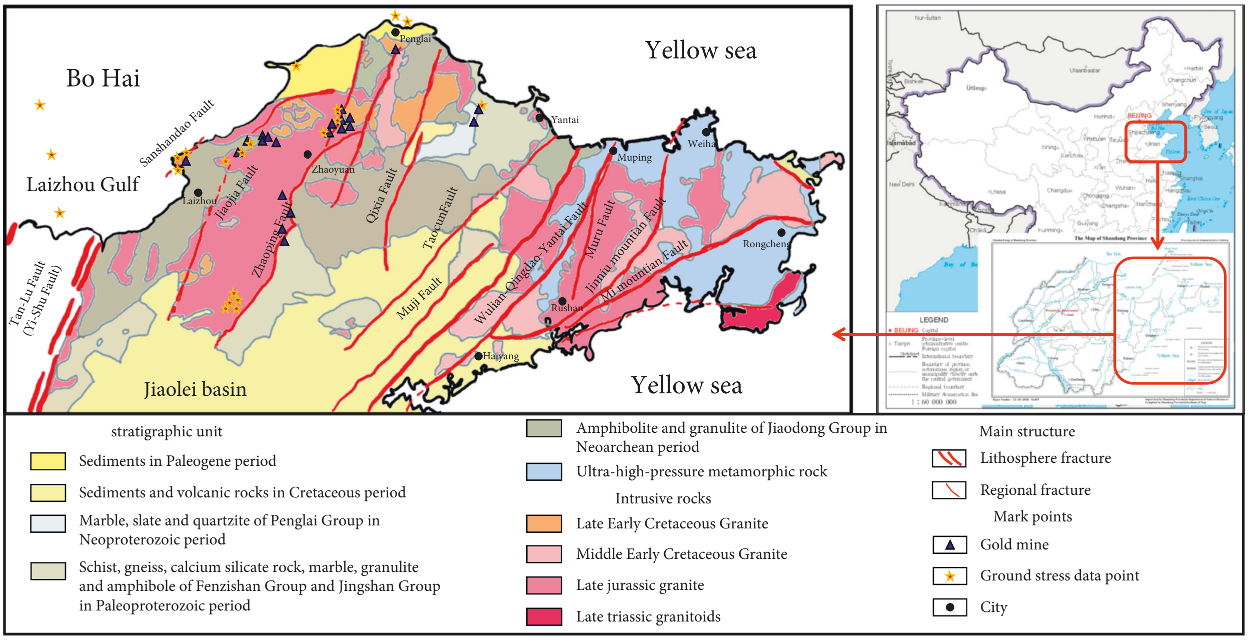


Figure 1: Outline diagram of the new structure in Shandong Province [10].

Figure 2: Current in situ stress zoning in China [25].

forming associated NWW-SEE dextral strike-slip faults and nearly S-N dextral strike-slip faults [33, 34]. The second period shows the transformation from NE-SW extrusion to NE-SW extension, which is reflected by the main positive fault in the Zhaoyuan-Pingdu fault band. The third period shows NW extension. The fourth period is near-E-W extrusion and near-S-N extension, and the NE direction fault in the region is mainly the right translation motion. In the field observation, a large number of E-W structures can be seen in the early stages of the extrusion structure. From the late Jurassic to the early Cretaceous period, Jiaodong plot shows the tectonic mechanical properties from extrusion to extension periodicity, the periodic change constantly changing and adjusting the stress field in the area [35, 36].

Through statistical analysis of the dominant direction of the maximum horizontal principal stress in the Jiaodong block, combined with the existing research results, it is found that the dominant direction of the maximum horizontal principal stress in the region is the NEE-SWW direction (consistent with the focal mechanism solution [37–39]).

4. The Law of In Situ Stress Distribution in the Northwest Jiaodong Peninsula

There are many places similar to the characteristics of seismic activity in the Shandong and North China blocks, among which the seismic activity of the two has a relatively significant correspondence in time [11]. However, due to the existence of the Tanlu fault zone, the Shandong region has its own particularity. Especially in the Jiaodong region, the difference between this region and the western Shandong region not only exists in stratum distribution but also in in situ stress. The following will be analyzed for the in situ stress distribution law in the northwest Jiaodong Peninsula.

4.1. Type Laws of In Situ Stress Field Distribution. Through the collection and measurement of data from the oil field, mine, geophysical research, and meteorological research, 164 items of in situ stress measurement data (depth from 4.7 m to 2300 m) were obtained by hydraulic fracturing methods and stress relief methods, as shown in Figure 3. The maximum horizontal principal stress in each group is greater than the vertical principal stress. It can be seen that the horizontal stress in the northwest Jiaodong Peninsula is dominant within the measurement depth, belonging to the typical structural stress field type. Among these, the magnitude relationship of three principal stresses in 40 groups was $\sigma_H > \sigma_h > \sigma_v$. Accounting for 24.4% of the total groups, they belong to the inverse fracture stress state, which is conducive to the gestation and activity of the inverse fault. The magnitude relationship of the three principal stresses in the remaining 124 groups is $\sigma_H > \sigma_v > \sigma_h$, accounting for 75.6% of the total number of groups, belongs to the slip stress state, and is conducive to the breeding and activity of the slip fault.

After analyzing the data by using the mathematical statistical analysis method, it is also found that when the depth is less than 300 m, the reverse-fault stress state dominates. In the depth range of 300 ~ 450 m, the distribution of the reverse fracture stress state is roughly equal to that of the strike-slip stress state. When the depth exceeds 450 m, the stress state is mainly a striking slip. It can be seen with the increase of depth that the vertical principal stress gradually changes from the minimum principal stress to the intermediate principal stress, and the stress state type gradually changes from the $\sigma_H > \sigma_h > \sigma_v$ to the $\sigma_H > \sigma_v > \sigma_h$.

4.2. The Variation Laws of Principal Stress with Depth. Since the vertical stress in the hydraulic fracturing data is estimated by the weight of the upper rock layer, only the data from the stress relief method are used to analyze the laws of vertical principal stress with depth. The relationship between the maximum horizontal principal stress, the minimum horizontal principal stress, and the vertical principal stress with depth is fitted by linear. The results are as follows:

$$\sigma_H = 0.0556H - 0.7772\,(\mathrm{R2} = 0.7924), \tag{1}$$

$$\sigma_v = 0.0346H - 1.6137\,(\mathrm{R2} = 0.9043), \tag{2}$$

$$\sigma_h = 0.0248H + 1.0504\,(\mathrm{R2} = 0.8319). \tag{3}$$

In the formula, H is the depth (m) and R is the correlation coefficient. The variation laws of principal stress with depth are shown in Figure 4. Due to the different aspects of geological conditions, topography, and rock properties, there is some dispersion of in situ stress measurement data. Equations (1)–(3) show that the correlation coefficient R2 of the three principal stress fitting equations is approximately greater than 0.8, with a high degree of linear correlation, indicates the approximate linear growth of in situ stress with the increase of depth, and also reflects the obvious change of the growth law of in situ stress from the depth range of meters to a few kilometers.

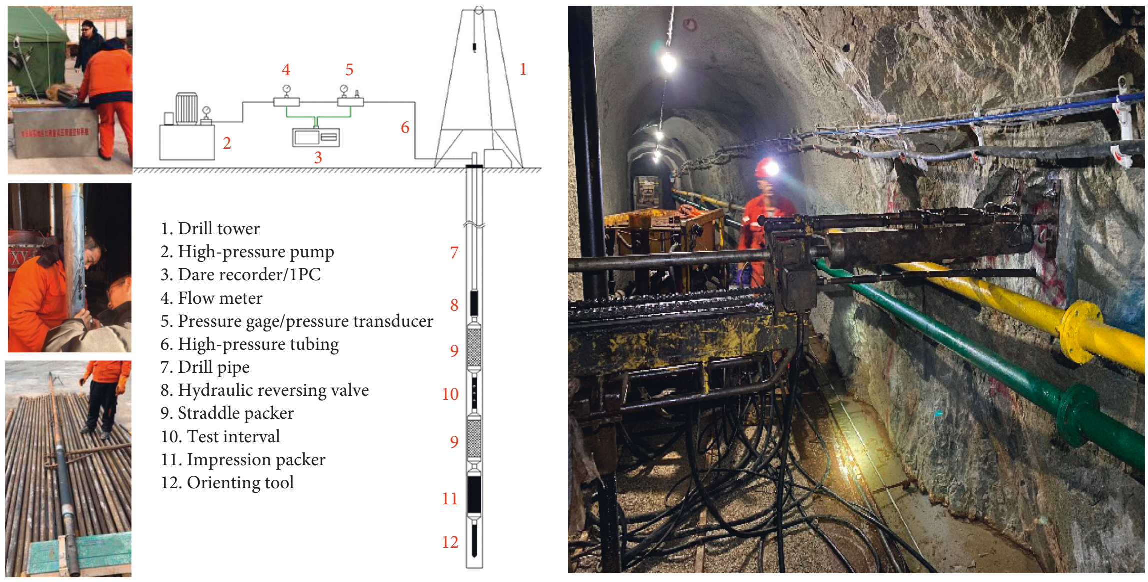
4.3. The Varies Laws Lateral Pressure Coefficient with the Depth. The lateral pressure coefficients are also widely used to characterize the in situ stress states at a point underground. Based on the ratio of σ_H, σ_h, $(\sigma_H + \sigma_h)/2$ with σ_v (collectively referred to the lateral pressure coefficient), the variation of in situ stress state with depth in the northwestern Jiaodong Peninsula is analyzed, which is denoted as KH, Kh, and Kav, respectively. The equations (4)–(6) of the three lateral pressure coefficients in hyperbolic form ($K = a/H +$, where a, b is the regression coefficient) are as follows:

$$K_{\mathrm{H}} = \frac{573.07}{H} + 0.2819, \tag{4}$$

$$K_h = \frac{397.32}{H} - 0.00283, \tag{5}$$

$$K_{\mathrm{av}} = \frac{379.47}{H} + 0.2069. \tag{6}$$

Figure 5 shows the distribution and fitting curves of the three lateral pressure coefficients with depth. As can be seen



(a) (b)

Figure 3: In situ stress measurement work. (a) Hydraulic fracturing method; (b) stress relief method.

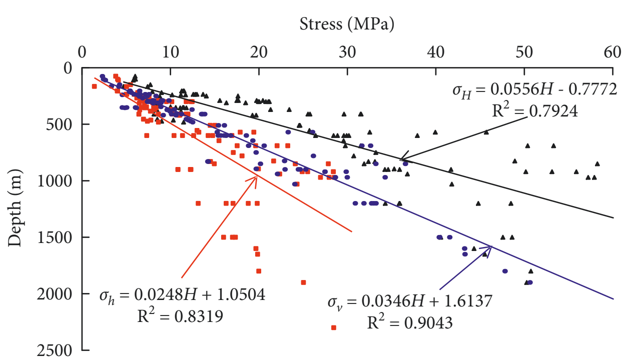


Figure 4: Variation of principal stress with depth.

from the figure, the distribution laws of K_H, K_h, and K_{av} are relatively discrete. The value of K_H is 0.68 to 4.76, average 1.99, the value of K_h is 0.39 to 2.91, average 1.12, and the value of K_{av} is 0.61 to 3.69, average 1.56.

Overall, both the dispersion and values of the three lateral pressure coefficients tended to decrease with increasing depth, whose changes were nonlinear. The results show that the three lateral pressure coefficients will likely tend towards a stable value with increasing depth. When $H < 1000$ m, the value of K_H is mostly greater than 2. When $1000 < H < 3500$ m, the range of K_H from 1.2 to 2.0 and the range of K_h from 0.5 to 1.0 are consistent with previous studies [40]. It can therefore be seen that in the shallow, tectonic stress is dominant, and as the depth increases, the in situ stress state gradually changes from the tectonic stress dominant state in the shallow part to the deep near hydrostatic pressure state.

4.4. The Variation Law of Relative Magnitude of Horizontal Differential Stress with Depth. The relative size of the horizontal difference stress μ_d ($\mu_d = (\sigma_H - \sigma_h)/(\sigma_H + \sigma_h)$) is a parameter related to the crust destruction state, which indicates the relative size of the maximum shear stress in the horizontal surface, which can reflect the crust shear stress state in the region to a certain extent. It is reasonable as the mechanical basis for judging the active fracture instability sliding. It can help better understand the characteristics of the tectonic stress field within the region. The results are as follows:

$$\mu_\mathrm{d} = \frac{536.58}{H} - 0.0389. \tag{7}$$

Figure 6 shows the distribution law of μ_d with depth. As can be seen from Figure 5, the distribution is relatively discrete. The range is 0.09 ~ 0.65, with an average value of 0.33, mainly concentrated in the range of 0.09 ~ 0.49. The range of value is 0.34 ~ 0.52 in the depths greater than 1500 m, with an average of 0.41. The range of value is 0.09 ~ 0.65 in the depth range of 0 ~ 1500 m, with an average of 0.32. It can be seen that the fluctuation range of the value less than 1500 m is larger, and the fluctuation range of the value gradually decreases with the increase in depth. Relevant research [41] shows that if the value in the crust exceeds 0.5 ~ 0.7, shear sliding failure may occur. Except for some data points, the value of the northwest Jiaodong Peninsula is basically 0.1~0.5. It can be inferred that under the current in situ stress state, the possibility of shear sliding failure of the faults in the region is small most of the time.

4.5. The Variation Law of Ratio of Horizontal Principal Stress Difference with Vertical Stress with Depth. The horizontal principal stress difference determines the shear stress in the rock mass. The relationship between the ratio of principal stress difference and vertical stress and depth is shown in

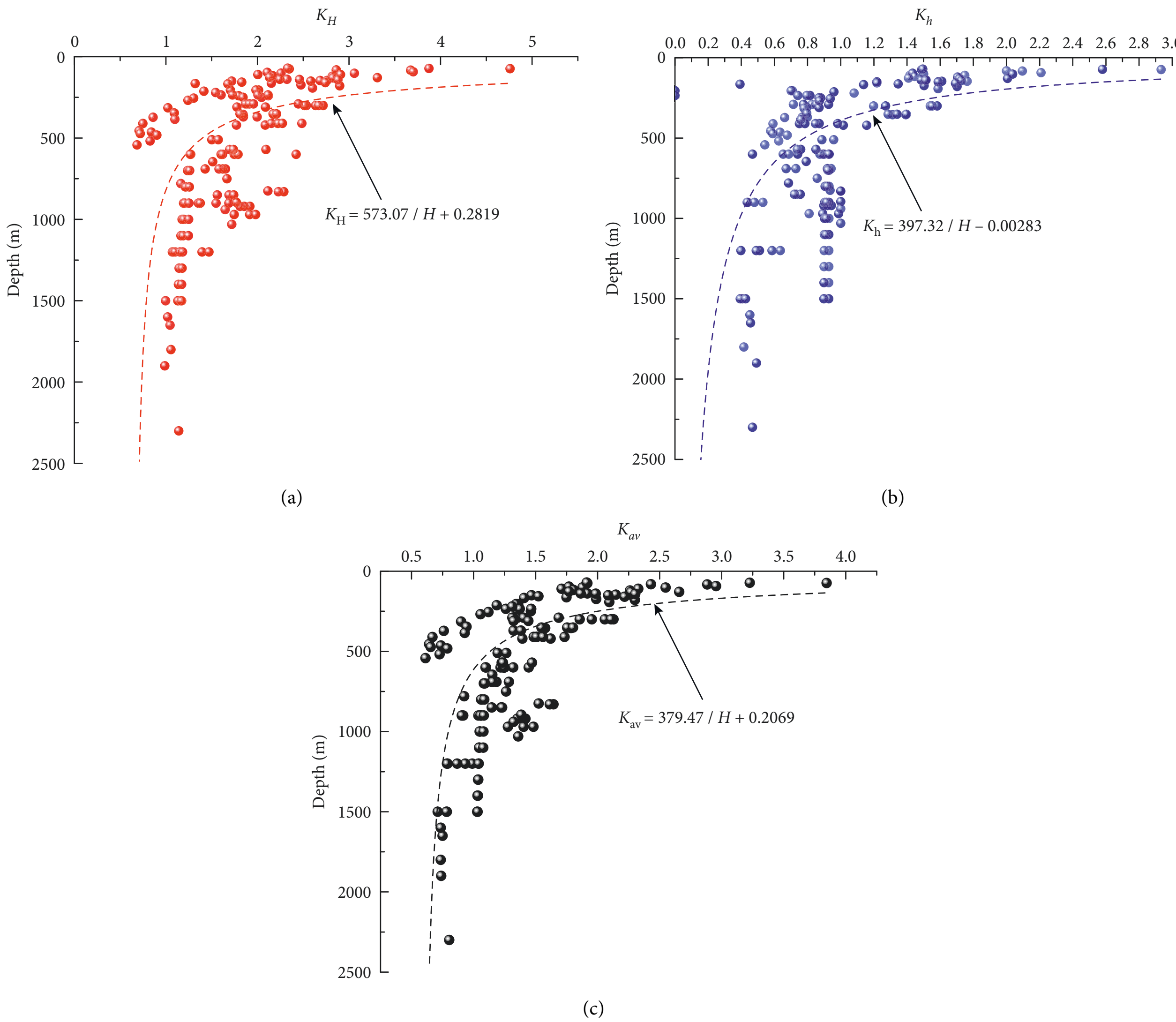


Figure 5: Distribution laws of lateral pressure coefficient with depth and fitting curve. (a–c) Maximum, minimum, and average horizontal lateral pressure coefficients with the depth, respectively.

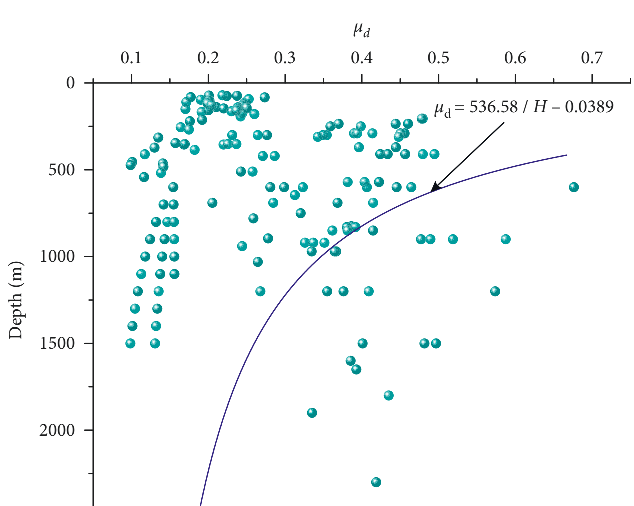


Figure 6: Relative magnitude of horizontal differential stress versus depth distribution and fitting curve.

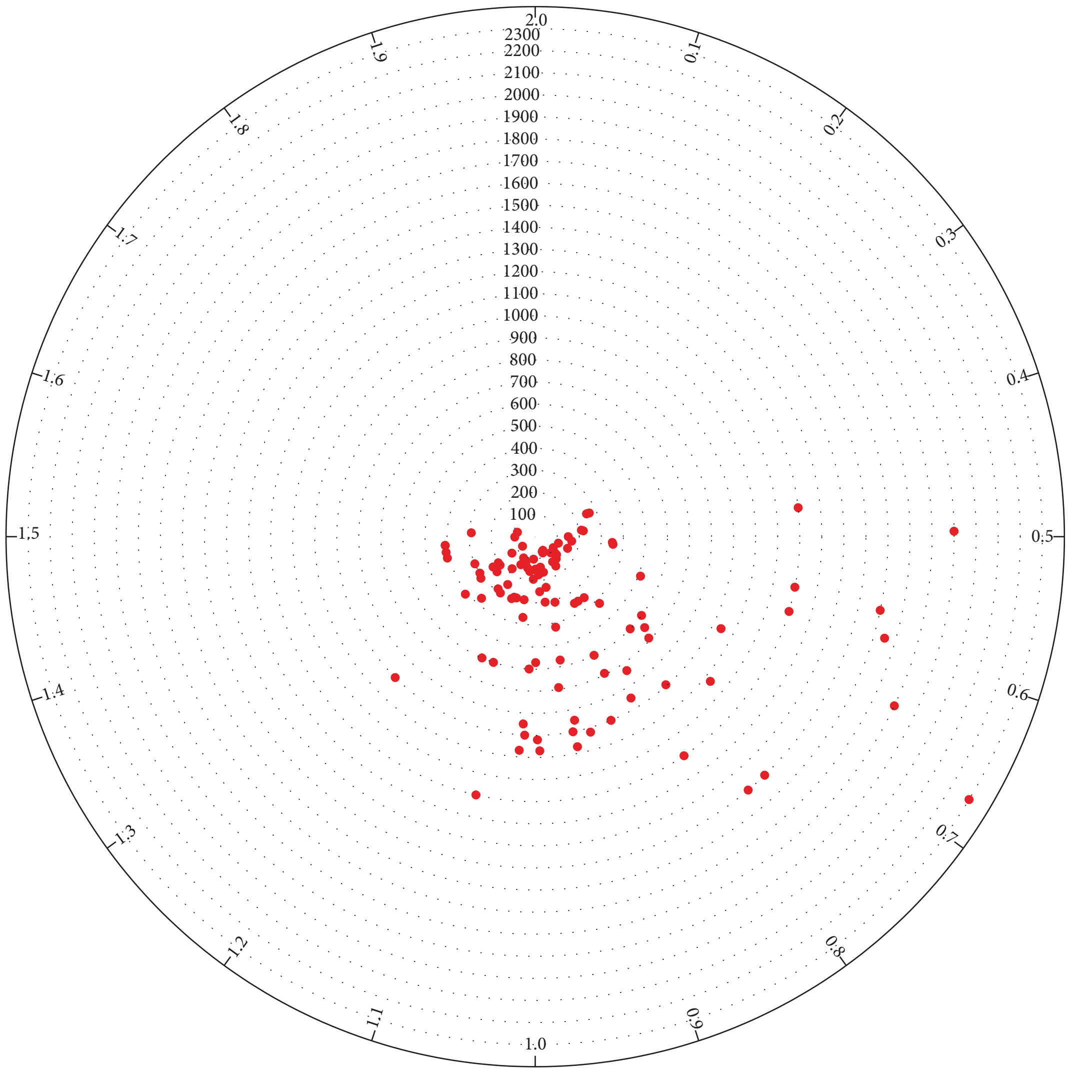


FIGURE 7: Distribution of the ratio of maximum and minimum principal stress difference and vertical stress with buried depth.

Figure 7. Shear failure is a common form of rock failure. The $K_{H\text{-}h}$ ratio of principal stress difference and vertical gradient is greater. The higher the shear stress of rock mass, the greater the probability of damage.

In all data points, the maximum $K_{H\text{-}h}$ value is 1.52, and the minimum value is 0.34. There are 18 data points where $K_{H\text{-}h} \leq 0.5$, accounting for 10.9% of the total. There are 146 data points where $0.5 < K_{H\text{-}h} \leq 1.1$, accounting for 73.2%, of which 120 are within $0.7 < K_{H\text{-}h} \leq 1.1$. There are 26 data points where $1.1 < K_{H\text{-}h} \leq 1.7$, accounting for 15.9%.

As shown in the above analysis and Figure 6, the $K_{H\text{-}h}$ of shallow ground is very discrete. With the development of the deep ground, $K_{H\text{-}h}$ is mostly concentrated between 0.7 and 1.0 in the range of 400 ~ 1000 m. The discreteness of $K_{H\text{-}h}$ gradually decreases in the range of 1000 ~ 2000 m, basically stable between 0.5 and 0.7. It is predicted through analysis that within a certain period of time, the rock mass can be guaranteed to be in a relatively stable state.

4.6. The Variation Law of Maximum Shear Stress with Depth. The maximum shear stress is 1/2 of the difference between the maximum and minimum principal stress, and the relationship with depth is shown in Figure 8. The relationship between maximum shear stress and depth is obtained by data regression,

$$\tau_m = \frac{\sigma_1 - \sigma_3}{2} = 0.014646H - 1.647993. \quad (8)$$

As can be seen from the figure, the maximum shear stress generally increases with depth. At the same time, an obvious discrete occurs. For all that, the discretization tends to decrease with depth. The reason for this phenomenon may be the scattered distribution of measuring points in the shallow, and these points are affected by the surface environment, coupled with the measurement results obtained by different methods which are quite different. So, the shallow shear stress distribution discretization is large. Although the number of measuring points in the deep is small, the distribution in the deep is more concentrated than that in the shallow, which greatly reduces the dispersion of the shear stress distribution.

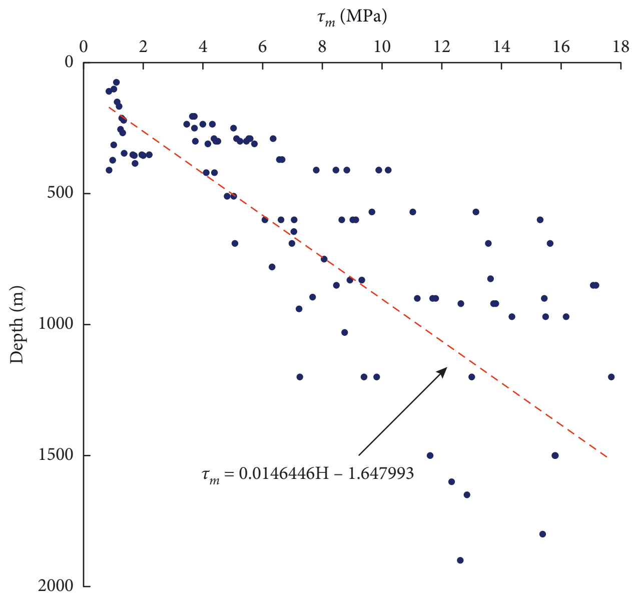


Figure 8: Distribution of maximum shear stress with depth and fitting curve.

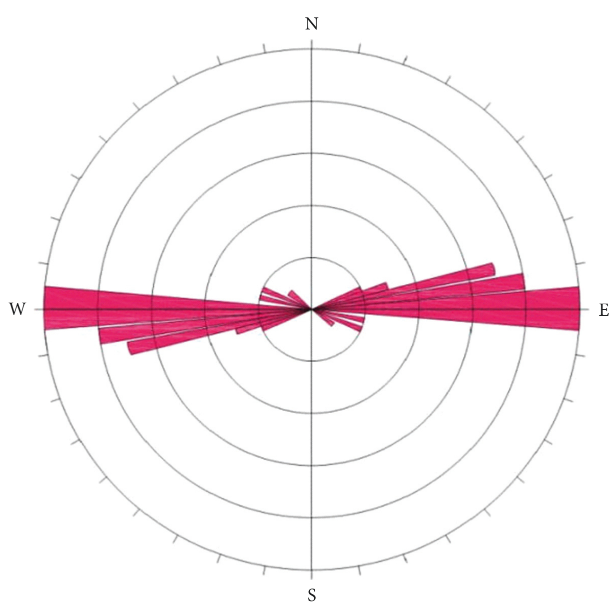


Figure 9: Distribution characteristics of the maximum horizontal principal stress direction in the northwest Jiaodong Peninsula.

4.7. The Distribution Characteristics of the Maximum Horizontal Principal Stress Direction. According to statistics, the maximum level of principal stress in the northwest Jiaodong Peninsula is generally close to EW and NEE-SWW, accounting for about 76.2% of the whole data, among which the near-E-W (70°~110°/250°~290°) is about 65.1%, the NEE-SWW about 11.1%, and the remaining directions about 23.8%. Figure 9 shows the rose chart of the direction of principal stress advantage in the northwest Jiaodong Peninsula. The figure shows that the overall direction of principal stress advantage in the northwest Jiaodong Peninsula is near E-W, and NWW-SEE also occupies a considerable proportion. This result is similar to the direction of the maximum horizontal principal stress in Shandong province, as shown in Figure 10 [10].

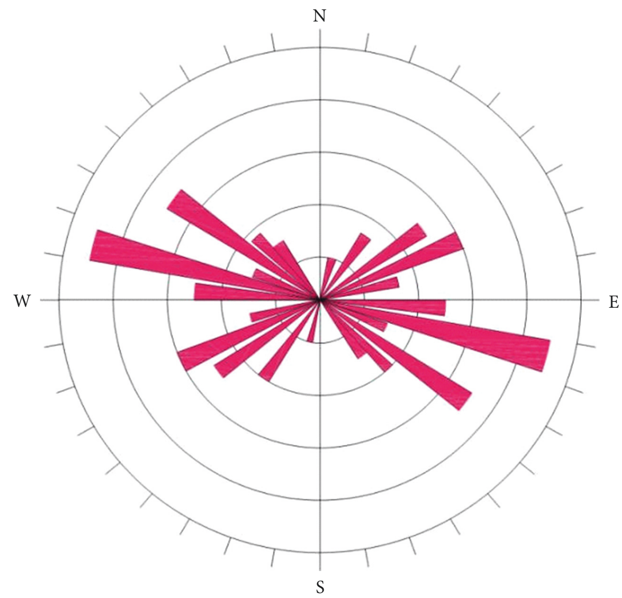


Figure 10: Distribution characteristics of the maximum horizontal principal stress direction in Shandong Provinces.

5. Conclusion

(1) By processing the 164 groups of data obtained by hydraulic fracturing methods and stress relief methods, the distribution law of the in situ stress field in the northwest Jiaodong Peninsula is got. The relationship among maximum principal stress, minimum principal stress, and vertical principal stress is analyzed by using the mathematical statistics method. In this area, the $\sigma_H > \sigma_h > \sigma_v$ gradually develops into the $\sigma_H > \sigma_v > \sigma_h$ below −450 m.

(2) The variation relationships of the maximum horizontal principal stress, the minimum horizontal principal stress, and the vertical principal stress with depth, respectively, are $\sigma_H = 0.0556H - 0.7772$, $\sigma_v = 0.0346H - 1.6137$, and $\sigma_h = 0.0248H + 1.0504$, respectively. The distribution laws of maximum, minimum, and average lateral pressure coefficients are in accordance with $K_H = 573.07/H + 0.2819$, $K_h = 397.32/H - 0.00283$, and $K_{av} = 379.47/H + 0.2069$.

(3) According to the obtained data, the relative magnitude of horizontal differential stress and the distribution law of maximum shear stress related to the fracture of surrounding rock are further studied, which are respectively $\mu_d = 536.58/H - 0.0389$ and $\tau_m = 0.014646H - 1.647993$. At the same time, it is also analyzed that the variation law of the ratio of horizontal principal stress difference with vertical

stress with depth concentrated in 0.7–1.0 at 400–1000 m and stabilized in 0.5–0.7 at 1000–2000 m. It is inferred that although the shear stress increases linearly with the increase of depth, there will be no shear dislocation failure in the rock stratum within 1500m.

(4) Through analysis, it is found that the directions of maximum horizontal principal stress in the northwestern Jiaodong Peninsula are EW and NEE-SWW, accounting for about 76.2% of all data [42].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was funded by Major Basic Projects in Shandong Province (ZR2021052400019) and the Major Science and Technology Innovation Project of Shandong Province (2019SDZY05).

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