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Distribution laws of in-situ stress in deep underground coal mines

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Abstract

With depth and intensity of coal mining increasing, effects of in-situ stress on deformation and failure of the surrounding rock are increasingly growing. Through data independently measured and collected within 600-1500m, this paper summaries distribution laws of in-situ stress in deep underground coal mines of our country, main existing types of in-situ stress and its directional characteristics. Maximum horizontal stress, minimum horizontal stress, vertical stress and lateral pressure ratio variation laws with depth are obtained by using regression analysis. Generally, in-situ stresses increase with depth. With increasing depth the rate of increase in horizontal stresses decreases. A considerable scatter in the in-situ stress test data may be due to distinct differences in both the strength and deformation moduli of strata located in varying geological environments and different coal districts. Two types of stress field distribution have been noted with \( \sigma_{Hv} \) (\( \sigma_{Hmax} > \sigma_v > \sigma_{hmin} \)) and \( \sigma_{Hv} \) (\( \sigma_v > \sigma_{Hmax} > \sigma_{hmin} \)) found mainly in deep coal mines. The ratio of the maximum horizontal principal stresses to vertical stress is usually between 0.63 and 2.42 in the deep coal districts.

Keywords: deep; coal mine; in-situ stress; stress field type; stress distribution characteristics

1. Introduction

While shallow coal resources of our country is reducing, coal mining is shifting to the deep with coal mining into the deep stage. Value of in-situ stress is growing, which damaging effects are increasingly significant and large deformation of roadway is not effectively control, which is a tremendous threat to safety and high yield of the coal business. For the mine project, in-situ stress is the fundamental force which generate mine power disaster and cause deformation and failure of the surrounding rock and also is the most important and fundamental factor which affects the stability of mining engineering[1-2].

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In-situ stress data of their respective deep area is less in almost every coal mine, which is lack of clear, accurate, complete understanding to distribution laws of deep in-situ stress. Many underground projects such as working face mining and support, the rock burst prevention, gas controlling without considering the direction and value of in-situ stress are designed, even in the case of non in-situ stress parameter, which cause roadway design and support unreasonable, severely damaged roadway, disasters not to be control effectively[3-4]. At the same time, in many numerical simulation on mechanical behavior of deep rock, for the value selection of in-situ stress, limited to lack of in-situ stress measured, only by self-weight stress calculation to determine and horizontal stress imposed by coefficient, results of the numerical simulation vary greatly with the actual, so true and reliable stress information is necessary.

2. In-situ stress data collection and collation

In order to obtain the distribution characteristics of in-situ stress field in deep mine, Beijing Mining Research Institute of China Coal Research Institute measures the in-situ stress in several deep mines, seeing Table1-3, meanwhile in order to gaining more statistical samples, the in-situ stress data of other research institutions are collected[5-12], which not listed, due to space limitations.

Table 1. Data of in-situ stress of HuaiNan deep mines (Hydraulic fracturing method)

| No. | Measuring point | Depth (m) | \(\sigma_v\) (MPa) | \(\sigma_{\text{imax}}\) (MPa) | \(\sigma_{\text{imin}}\) (MPa) | direction of \(\sigma_{\text{imax}}\) |
|-----|----------------|-----------|-------------------|-----------------|-----------------|-----------------|
| 1   | Xieyi mine     | 803.00    | 20.08             | 16.90           | 8.93            | N46.2°W         |
| 2   | Xieyi mine     | 802.00    | 20.05             | 19.99           | 10.51           | N42.3°W         |
| 3   | Xieyi mine     | 655.00    | 16.38             | 13.36           | 6.94            | N30.2°E         |
| 4   | Xieyi mine     | 740.00    | 18.50             | 19.85           | 10.38           | N33.3°E         |
| 5   | Pansan mine    | 735.00    | 18.38             | 16.24           | 8.52            | N84.7°E         |
| 6   | Xieqiao mine   | 740.00    | 18.50             | 13.74           | 7.09            | N35.7°W         |

Table 2. Data of in-situ stress of Xinwen deep mines (Hydraulic fracturing method)

| No. | Measuring point | Depth (m) | \(\sigma_v\) (MPa) | \(\sigma_{\text{imax}}\) (MPa) | \(\sigma_{\text{imin}}\) (MPa) | direction of \(\sigma_{\text{imax}}\) |
|-----|----------------|-----------|-------------------|-----------------|-----------------|-----------------|
| 1   | HuaFeng mine   | 1220.00   | 30.50             | 42.19           | 22.80           | N3.0°E          |
| 2   | HuaFeng mine   | 1130.00   | 28.25             | 33.15           | 19.10           | N31.5°E         |
| 3   | HuaFeng mine   | 1040.00   | 26.00             | 31.35           | 16.20           | N23.5°W         |
| 4   | PanXi mine     | 964.00    | 24.10             | 25.65           | 12.23           | N32.3°E         |
| 5   | PanXi mine     | 967.00    | 24.18             | 21.42           | 10.87           | N43.5°E         |
| 6   | PanXi mine     | 961.00    | 24.03             | 20.06           | 10.12           | N25.9°E         |
| 7   | SunChun mine   | 1283.00   | 32.08             | 31.97           | 16.51           | N20.6°E         |
| 8   | SunChun mine   | 982.00    | 24.55             | 33.12           | 16.80           | N35°E           |
| 9   | SunChun mine   | 1034.00   | 25.85             | 23.22           | 12.19           | N23.5°W         |
| 10  | XieZhuang Mine | 790.00    | 19.75             | 32.39           | 16.56           | N33.5°E         |
| 11  | XieZhuang Mine | 1150.00   | 28.75             | 34.60           | 17.89           | N12.5°          |
| 12  | XieZhuang Mine | 1071.00   | 26.78             | 39.77           | 20.60           | N39.7°E         |
Table 3. Data of in-situ stress of Ping Dingshan deep mines (Hydraulic fracturing method)

| No. | Measuring point | Depth (m) | \(\sigma_v\) (MPa) | \(\sigma_{\text{Hmax}}\) (MPa) | \(\sigma_{\text{Hmin}}\) (MPa) | direction of \(\sigma_{\text{Hmax}}\) |
|-----|----------------|----------|-----------------|-----------------|-----------------|---------------------|
| 1   | Five mine      | 844.03   | 21.10           | 13.10           | 8.16            | N61°E               |
| 2   | Five mine      | 718.24   | 17.96           | 12.80           | 6.96            | N61.8°W             |
| 3   | Five mine      | 718.24   | 17.96           | 10.76           | 5.84            | N70.6°W             |
| 4   | Eleven mine    | 689.70   | 17.24           | 13.61           | 8.25            | N61.8°W             |
| 5   | Eleven mine    | 742.95   | 18.57           | 13.28           | 8.14            | N57°W               |
| 6   | Eleven mine    | 763.20   | 19.08           | 13.98           | 8.84            | N39°E               |

Note, vertical stress calculated by bulk density of the overlying rocks

3. Types of in-situ stress field in deep mines

At present, in the research on coal mining, generally according to the relationship of the values of the three principal, which are maximum horizontal stress \(\sigma_{\text{Hmax}}\), minimum horizontal stress \(\sigma_{\text{Hmin}}\), vertical stress \(\sigma_v\), in-situ stress field is divided to three different types, which is

\[
\sigma_{\text{Hhv}}, \quad \sigma_{\text{Hmax}} > \sigma_{\text{Hmin}} > \sigma_v
\]

\[
\sigma_{\text{Hvh}}, \quad \sigma_{\text{Hmax}} > \sigma_v > \sigma_{\text{Hmin}}
\]

\[
\sigma_{\text{vHh}}, \quad \sigma_v > \sigma_{\text{Hmax}} > \sigma_{\text{Hmin}}
\]

The types of \(\sigma_{\text{Hhv}}\) and \(\sigma_{\text{Hvh}}\) are the stress field that horizontal stress is dominant, often referred as tectonics stress field. The type of \(\sigma_{\text{vHh}}\) is the stress field that vertical stress is dominant, often referred as gravity stress field. The impact to roadway of the different types of in-situ stress field is different. High horizontal stress and high vertical stress are received equally attention.

By analyzing those in-situ stress data, the stress field types of several major deep mines in China have the following characteristics. The types of \(\sigma_{\text{Hhv}}\) and \(\sigma_{\text{Hvh}}\) exist in XinWen mine, which \(\sigma_{\text{Hhv}}\) is dominant and doesn’t have the type of \(\sigma_{\text{Hvh}}\). The types of \(\sigma_{\text{Hvh}}\) and \(\sigma_{\text{vHh}}\) in HuaiNan mine, which \(\sigma_{\text{vHh}}\) is dominant, not having the type of \(\sigma_{\text{Hhv}}\). The types of \(\sigma_{\text{Hvh}}\) and \(\sigma_{\text{vHh}}\) exist in Ping Dingshan mine, which \(\sigma_{\text{vHh}}\) is dominant and doesn’t have the type \(\sigma_{\text{Hhv}}\).

Those show that In the deep mines below 600m, the types of \(\sigma_{\text{Hhv}}\) and \(\sigma_{\text{vHh}}\) stress field are main types of stress field, but in the same mine zone two types of in-situ stress maybe exist, which are dominant according to measure data to determine. The type of \(\sigma_{\text{Hhv}}\) isn’t found in deep mines.

4. Value feature of in-situ stress in deep coal mines

Currently, the in-situ stress fields are divided into three types, ultrahigh stress field, high stress field, and low stress field. The value of maximum principal stress more than 40MPa is classified as ultrahigh stress field, between 20MPa to 40MPa as high stress field, less than as low stress field. With depth more than 600m, the value of in-situ stress is more and more high, and most coal mines will be in high or ultrahigh stress field. Table 1-3 shows the value of in-situ stress is between 20MPa to 40MPa in deep coal mines between 600m to 1500m which belongs to high stress field.

4.1. Relationship of horizontal stress variation with depth

Distribution laws of maximum horizontal stress \(\sigma_{\text{Hmax}}\) and minimum horizontal stress \(\sigma_{\text{Hmin}}\) with depth are shown in Figure 1 and Figure 2, which statistics depth is between the shallow 652m to the deep 1283m. It can be seen that the value of maximum horizontal stress is between 20Mpa to 50MPa, the value
of minimum horizontal stress between 10MPa to 30MPa. $\sigma_{Hmax}$ and $\sigma_{hmin}$ generally increase with depth, which relationship is a linear one with the change of depth. Scatters basically vary between two dotted lines, and this band reflect the difference of two horizontal stress at same depth in different coal mine areas of our country, which is caused by the difference of tectonic movement in different deep coal mine area.

Regression formula of maximum horizontal stress:

$$\sigma_{Hmax} = 0.023h + 11.14$$  \hspace{1cm} (1)

Regression formula of minimum horizontal stress:

$$\sigma_{hmin} = 0.018h + 1.84$$  \hspace{1cm} (2)

It can be seen that the maximum horizontal stress gradient is 0.023MPa/m, the maximum horizontal stress gradient is 0.018MPa/m. if the above data is grouped according to the aforementioned method, and stress data of different type separately are regressed, it can be found that the stress gradient of $\sigma_{Hmax}$ and $\sigma_{hmin}$ are greater than rock bulk density in $\sigma_{Hhv}$.

Fig. 1. scatters of maximum horizontal stress variation with depth

Fig. 2. scatters of minimum horizontal stress variation with depth
4.2. Ratio of maximum horizontal stress and minimum horizontal stress variation with depth

Maximum horizontal stress and minimum horizontal stress has no obvious relationship. Figure 3 shows that the ratio between the two is 1.5 to 2.5, which 5% of the measuring point is located between 1.0 to 1.2, 43% between 1.2 to 1.4, 52% greater than 1.4. In the same depth level, the ratio changes from 1 to 2.5, which shows that tectonic movement in the same depth level in different coal mines are different. The ratio is close to 1 in some coal mines, which shows that those areas are in the state of hydrostatic pressure, such as Kongzhuang coal mine.

Range of the ratio of $\sigma_{\text{Hmax}} / \sigma_{\text{Hmin}}$:

$$1.05 < \frac{\sigma_{\text{Hmax}}}{\sigma_{\text{Hmin}}} < 2.50$$ (3)

Fitting formula of all points:

$$\frac{\sigma_{\text{Hmax}}}{\sigma_{\text{Hmin}}} = \frac{320}{H} + 1.224$$ (4)

The absolute difference of maximum horizontal stress and minimum horizontal stress in the same point is between 5MPa to 20MPa, and the relationship between the two is not obvious, which have no significant relationship. The difference value is small in shallow areas. The ratio has an important significance to research on the role of horizontal tectonic stress.

4.3. Relationship of vertical stress variation with depth

Studies have shown that vertical stress basically equal to the weight of unit area of overlying rock where geological structure is not developed. In geological structure developed, the vertical is small even in deep coal mines. The vertical stress in Hydraulic fracturing is calculated according to the weight of overlying rock. In the stress data of stress relief method, there is always a principal stress in the vertical direction. The bulk density of the overlying rock is 2500t/m$^3$. The factor 1.5 derived from Formula 4 is almost approaching the value which Heok and Brown have got. Relationship of vertical stress variation with depth is as follow.
Fig. 4. Relationship of vertical stress variation with depth

Regression formula:

\[ \sigma_v = 0.0245h + 1.78 \]  

(5)

4.4. Ratio of horizontal stress and vertical stress variation with depth

Ratio of average horizontal stress and vertical stress is from 0.64 to 2.03, shown in Figure 5, 80% of the ratio is from 0.5 to 1.5 and 20% greater than 1.5. The ratio is close to as the depth increases. The lateral pressure ratio, which is the ratio of maximum principal stress and vertical stress, shown in Figure 6,
Fig. 6. ratios of maximum principal stress and vertical stress
is from 0.63 to 2.42, which 20% of the ratio is less than 1 and 80% greater than 1. This shows that the horizontal stress is the dominant stress in most deep coal mines, which match to the shallow earth crust movement.

5. Directional characteristics of in-situ stress in deep coal mines

The horizontal stress in rock layers has obvious direction characteristics, which has the significant difference between different regions and both and deep are both so. Several stress direction information can easily be obtained by field measure, but the general direction information is difficult to be determined. In past, the average stress orientation information is as regional principal stress direction, which approach is questionable.

Based on data measured in different ways, and through testing and validation by geomechanical analysis, the relatively scientific and reasonable information to the stress direction can be obtained.

In short, the stress direction of the specific regions should be directed from the specific analysis, comprehensive analysis, measured priority, geomechanical analysis. Figure 7 to 9 are respectively the direction rose diagram of Xinwen mine, Huainan mine and Pingdingshan mine, which show that the dominant direction of in-situ stress of different coal mines and are very different.

Fig. 7. direction rose diagram of Xinwen mine
6. Conclusions

The $\sigma_{Hvh}$ and $\sigma_{vHh}$ stress field type appears mainly in deep coal mines (600-1500m). The $\sigma_{Hhv}$ stress field type rarely appears. The stress type of specific regions must be measured.

Overall, in-situ stresses increase with depth in deep underground coal mines. In deep coal mines, the rates of increase in horizontal stresses are less than that of vertical stress, and then gradually decease in depth. The ratio of maximum horizontal to vertical stress tends to decrease and approaches 1 with increasing depth.

The direction of horizontal stress is obvious. The stress directional of the specific regions should be obtained from field measure.

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