Influence of complex geological conditions on the in situ stress field of the SK Hydropower Station in Pakistan

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Abstract. The Suki–Kinari hydropower station is situated in a landform with high mountains and deep valleys in northwest Pakistan. Affected by some geological conditions such as topography and faults, the in situ stress distribution of the project area is highly complex. To determine the in situ stress associated with this project, hydraulic fracturing in situ stress tests are conducted in four representative boreholes. Generally, the relation of the three principal stresses is \( \sigma_1 > \sigma_2 > \sigma_3 \). However, the measured stress directions associated with the headrace tunnel and the powerhouse area are clearly different. The direction of the maximum horizontal principal stress of the headrace tunnel is NNE–NEE, whereas that of the underground powerhouse area is NNW–NWW. To identify the mechanism responsible for this difference, the present study simulates the stress field in the project area based on the three-dimensional finite element regression analysis method. Two theories are proposed on the basis of the numerical simulation results. On the one hand, the direction of the maximum horizontal principal stress in the rock mass above the valley elevation is controlled mainly by topography. On the other hand, the fault will disturb the stress field, causing noticeable changes in the stress direction and value of the fault-affected zone. By comparing the characteristics of the stress direction distribution at three elevations, the direction of maximum horizontal principal stress of the shallow strata is determined to be affected mainly by the topography and faults, and topography may be the most important factor. Moreover, with an increase in strata depth, the influence of the topography and faults on the stress direction decreases gradually. After reaching a particular strata depth, the direction of maximum horizontal principal stress tends to be the same as that of the regional tectonic stress, i.e., NNE.

1. Introduction

In case of underground projects, it is highly important to ascertain the distribution characteristics of the in situ stress field. Field testing is the most direct and effective method for obtaining the in situ stress. However, owing to budget constraints, it is impossible to conduct a large number of tests. Therefore, numerical simulation has become the most effective research method of stress fields based on the limited amounts of measured stress data. Currently, the commonly used numerical analysis methods for in situ stress include boundary load adjustment, the stress (displacement) function,
multiple linear regression analysis, displacement back analysis, and neural networks\textsuperscript{[1,2]}. Various methods can be used jointly to achieve better simulation results and compensate for any limitations.

The lengths and burial depths of underground caverns are currently increasing. Thus, it is inevitable to encounter complex geological conditions such as large topographical undulations, complex strata lithology, and fault development areas. The in situ stress near these areas become extremely complicated, which may cause numerous obstacles in project designs and construction. Therefore, many scholars have researched the factors that can affect the in situ stress field. Zhu\textsuperscript{[3]} and Qi\textsuperscript{[4]} revealed the stress distribution characteristics of a deep-cut valley through field tests and numerical simulation. Huang\textsuperscript{[5]} conducted continuous research on the stress characteristics and evolution of a steep slope. Su\textsuperscript{[6]} studied the influence of active faults on a stress field by analyzing the measured stress data. The above research is based on single factors; however, the characteristics of steep slopes, deep valleys, and fault development occur together at the Suki–Kinari hydropower station. Therefore, the present study examines the stress field distribution under the influence of multiple factors.

The Suki–Kinari hydropower station is situated on the Kunhar River in northwestern Pakistan, which has complicated geology. To study the differences in stress occurring in the powerhouse and headrace tunnel areas, the in situ stress field of the project area is simulated by using multiple linear regression analysis based on the measured stress data. The results reveal the causes of the stress difference and are used to further summarize the stress characteristics and typical topography in a fault development area.

2. Tectonic geological background

Affected by its collision with the Eurasian plate 50–55 million years ago, the Indian plate subducted in the lower part of the Eurasian plate to form a complex geological environment.

From the Indus Valley to the Brahmaputra Valley, the Himalayas are distributed from east to west, forming a gentle arc area with a length about 2,400 km. The axis of the arc zone extends to the south of the proposed project area, and the geological tectonics form a closed ring zone known as the Hazara–Kashmir merge zone. Figure 1 maps the focal mechanism of the northwestern Himalayas and adjacent areas. Located mainly in the collision zone between the Indian plate and the Himalayas, the project area was squeezed by the NNE direction of the Indian plate and was then blocked by the Himalayas. The multiple seismic focal mechanism solutions in figure 1 reflect that the project area is under the action of horizontal compressive stress in the NNE–NE direction, and most of the seismogenic faults are thrust faults.

![Figure 1. Focal mechanism solution in the northwest Himalayas and adjacent areas](image-url)
3. Research of in situ stress test results in the project area

The hydraulic fracturing method, recommended by the Test Method Committee of the International Society of Rock Mechanics in 1987 for measuring rock stress, is used for direct testing of in situ stress\(^7\). Because calculation of test results does not require rock elastic parameters, the error caused by inaccurate rock elastic parameter values is avoided. Moreover, this method is easily operated and has a short test period. According to the test requirements for hydraulic fracturing, we selected an intact rock and a smooth borehole wall as the stress test segment in the four boreholes. The stress test results are shown in table 1, whereas the layout of boreholes and geological conditions are shown in figure 2.

| B.H.\(^a\) | \(H^b\) /m | \(\sigma_{H^c}\) /MPa | \(\sigma_{p^d}\) /MPa | \(\sigma_{z^e}\) /MPa | \(\lambda^f\) | \(\alpha_{H^g}\) /º |
|-----------|------------|-----------------|-----------------|-----------------|--------|---------------|
| ZKC1      | 229        | 7.5             | 5.0             | 6.3             | 1.2    | 15            |
|           | 248        | 8.0             | 5.1             | 6.8             | 1.2    |               |
|           | 282        | 10.8            | 6.1             | 7.8             | 1.4    | 22            |
|           | 301        | 11.2            | 7.0             | 8.3             | 1.4    |               |
|           | 319        | 11.8            | 6.8             | 8.8             | 1.3    | 34            |
|           | 336        | 12.3            | 7.1             | 9.3             | 1.3    |               |
| ZKC13     | 244        | 7.5             | 4.3             | 6.5             | 1.1    | 328           |
|           | 250        | 8.2             | 4.8             | 6.7             | 1.2    | 332           |
|           | 262        | 8.3             | 4.7             | 7.0             | 1.2    | 313           |
|           | 269        | 8.4             | 5.1             | 7.2             | 1.2    | 356           |
|           | 277        | 9.5             | 5.5             | 7.4             | 1.3    | 320           |
| ZKC2      | 260        | 13.4            | 8.1             | 7.2             | 1.9    | 78            |
|           | 310        | 11.2            | 8.3             | 8.5             | 1.3    |               |
|           | 330        | 13.1            | 8.7             | 9.1             | 1.4    | 82            |
|           | 336        | 13.3            | 9.6             | 9.2             | 1.4    |               |
|           | 351        | 13.8            | 8.8             | 9.7             | 1.4    | 64            |
|           | 367        | 15.5            | 10.5            | 10.1            | 1.5    |               |
| ZKC18     | 331        | 9.9             | 5.8             | 8.8             | 1.1    | 294           |
|           | 389        | 10.4            | 6.9             | 10.4            | 1.0    | 309           |
|           | 435        | 12.2            | 8.3             | 11.6            | 1.0    | 298           |
|           | 440        | 14.3            | 9.5             | 11.7            | 1.2    |               |
|           | 446        | 12.3            | 8.6             | 11.9            | 1.0    | 322           |
|           | 463        | 13.3            | 8.2             | 12.4            | 1.1    |               |

\(^a\) Borehole number; \(^b\) test depth; \(^c\) maximum horizontal principal stress; \(^d\) minimum horizontal principal stress; \(^e\) gravity stress of overlying strata; \(^f\) lateral compression coefficient of maximum horizontal principal stress \((\sigma_{H}/\sigma_{z})\); \(^g\) maximum horizontal principal stress direction based on the geodetic coordinate system, where 0° (360°) is the north direction, and the azimuth rotates clockwise.

As shown in the figure, the ZKC1 and ZKC3 boreholes are located in a NE-oriented mountain, whereas the ZKC13 and ZKC18 boreholes are located in a NW-oriented mountain. The two mountains are separated by a S–N-oriented valley.
Figure 2. Borehole layout and geological conditions

The test depth of the ZKC1 borehole, which is located in a high–steep slope, does not exceed the elevation of the slope foot. The tested rock mass is a quartz mica schist with good integrity and long column cores. As shown in table 1, the lateral pressure coefficient $\lambda$ of the maximum horizontal principal stress is 1.2–1.4, and the maximum horizontal principal stress direction $\alpha_H$ is NNE. According to the results of the mechanical mechanism analysis, the high–steep slope rock is close to the free face, and the stress is usually released in the direction perpendicular to the free face. Therefore, the closer to the side slope surface, the lower the horizontal stress value. Correspondingly, $\alpha_H$ is parallel to the slope strike; thus, the stress of the ZKC1 borehole is affected mainly by the side slope topography.

The ZKC2 borehole is located in the influence zone of regional active fault F18 striking NEE, and its test depth is near the valley elevation. The test rock is also a quartz mica schist with long column cores. In this borehole, $\lambda = 1.3–1.9$, which is obviously larger than that of ZKC1 borehole. This difference is related to the stress concentration phenomenon occurring at the bottom of the valley. According to the Anderson fault model, $\alpha_H$ should be perpendicular to the reverse fault strike, although the test direction is NEE, which approximately parallel to the fault strike. Geological survey records indicate that the rock mass of the shallow strata in the F18 fault zone is broken. Thus, the fragmentation of the shallow rock mass in the fault zone during the tectonic activity released part of its initial stress, which hindered the stress transfer perpendicular to the fault strike. Thus, $\alpha_H$ was gradually adjusted and is nearly parallel to the fault strike.

Similar to the environment of the ZKC1 borehole, the ZKC13 borehole is also located in a high–steep slope, and the test rock mass is also a quartz mica schist but with developed fissures. Therefore,
affected by the side slope topography and rock fissures, \( \lambda = 1.1-1.3 \) in this borehole, and \( \alpha_H \) is NNW–NW.

The ZKC18 borehole is on a gentle ridge close to the regional active fault F25-1 striking E–W. The test rock mass is a metamorphic gravelly quartzite with developed fissures. Affected by the lithological changes, developed fissures, and fault F25-1, \( \lambda = 1.0–1.2 \) in this borehole. Compared with the other three boreholes, its stress value in this borehole is minimal. Under the influence of the NW strike slope and E–W strike fault, \( \alpha_H \) is NW–NWW.

The test results indicate that the in situ stress characteristics of the shallow strata are related mainly to the topography and faults. A comparison of boreholes ZKC1 and ZKC2 revealed clear differences in the stress values between the high–steep slope and the valley. Compared with borehole ZKC13 and ZKC18, the fault caused a decrease in the stress value in its affected area. According to the stress direction, \( \alpha_H \) in the shallow strata is controlled mainly by the topographical conditions. For example, under the influence of different topography, the \( \alpha_H \) values of boreholes ZKC1 and ZKC2 are obviously different from those of boreholes ZKC13 and ZKC18. Moreover, the fault has a significant disturbance effect on \( \alpha_H \) in the shallow strata, such as that in boreholes ZKC2 and ZKC18. Generally, however, the topographical conditions play a dominant role in the formation of the stress direction in shallow strata.

4. Finite element regression analysis of in situ stress field in the project area

To establish a three-dimensional finite element model, geological conditions such as topography, formation lithology and fault distribution need to be generalized. For the convenience of modeling, east is taken as the positive direction of the X-axis, north is taken as the positive direction of the Y-axis in the geodetic coordinate system, and the positive direction of the Z-axis is vertical upward. The calculation range of the X–Y plane is 3,000 m × 4,500 m, and the bottom elevation is 500 m. The finite element calculation model is shown in figure 3. The main lithology is simplified as a quartz mica schist with seven faults. According to the geological characteristics of the rock mass, the hardness and strength of the quartz mica schist are far greater than those of the fault zone rock mass. Thus, to better reflect the stress adjustment caused by fault zone deformation, the quartz mica schist and fault are defined as elastic and elastic–plastic materials, respectively. The mechanical parameters of two types of rock samples were tested in the laboratory; the recommended parameters are shown in table 2.

| Lithology             | Bulk density (kN/m³) | Deformation modulus (GPa) | Poisson’s ratio | Internal friction angle (°) | Cohesion (MPa) |
|-----------------------|----------------------|---------------------------|-----------------|----------------------------|----------------|
| Quartz mica schist    | 27.6                 | 13                        | 0.13            | -                          | -              |
| Fault                 | 19                   | 1.2                       | 0.4             | 23                         | 0.12           |

In this study, the multiple regression analysis method\(^{2,8,9}\) was used for simulating the stress field. The measured stress was transformed into six stress component values under the calculation coordinate system. The stress regression calculation value was taken as the dependent variable, and the calculated value of the gravity stress field and the tectonic stress fields obtained by finite element calculation corresponding to the measured point was taken as the independent variable. Then, the regression equation is expressed as
\[ \hat{\sigma}_k = \sum_{i=1}^{n} L_i \sigma_{ik}^i, \]

where \( k \) is the serial number of the observation point, \( \hat{\sigma}_k \) is the regression calculation value of the \( k \)-th observation point, \( L_i \) is the multiple regression coefficient corresponding to the independent variable, \( \hat{\sigma}_k \) and \( \sigma_{ik}^i \) are the single-column matrices of the corresponding stress component calculation value, and \( n \) is the number of working conditions.

Assuming that there are \( m \) observation points, the residual sum of squares in the least squares method represents the degree of deviation and can be written as

\[ S_{\text{residual}} = \sum_{k=1}^{m} \sum_{j=1}^{6} (\sigma_{jk}^o - \sum_{i=1}^{n} L_i \sigma_{ik}^i)^2, \]

where \( \sigma_{jk}^o \) is the observed value of stress component \( j \) of observation point \( k \), and \( \sigma_{ik}^i \) is the finite element calculation value of stress component \( j \) of observation point \( k \) under condition \( i \).

According to the principle of the least squares method, the minimum residual sum of squares is calculated, and undetermined regression coefficients \( L = [L_1, L_2, \ldots, L_n]^T \) can be obtained. Then the regression stress at any point \( P \) in the calculation domain is

\[ \sigma_{jp} = \sum_{i=1}^{n} L_i \sigma_{jp}^i, \]

where \( j = 1, 2, \ldots, 6 \) corresponds to the six components of the initial stress.

**Figure 3.** Finite element calculation mesh model

**Figure 4.** Load application and boundary constraints

Regarding the geomechanical perspective, the in situ stress field is composed mainly of a gravity stress field and a tectonic stress field. The in situ stress field in the computational domain is regarded as the linear superposition of these two stress fields applied at the boundary. The gravity stress field is the vertical stress calculated by the rock mass density, and the tectonic stress, approximately horizontal, is caused by compression and shearing in the X- and Y-axis directions. After trial calculation and comparison, the loading mode shown in figure 4 was adopted.
According to the measured stress and multiple regression analysis of the least squares method, we determined the regression coefficient for the four independent variables as $L_a = 1.03$, $L_s = 0.52$, $L_y = 0.76$, and $L_{xy} = 0.12$ corresponding to gravity stress, X-axis tectonic stress, Y-axis tectonic stress, and horizontal shear stress, respectively. In the X–Y plane, $L_a$, $L_s$, and $L_{xy}$ can be regarded as the loading stress on the unit load. After the formula conversion between the plane and principal stresses, the direction of the maximum principal stress in the X–Y plane was determined to be N23°E, which is consistent with the tectonic principal compressive stress direction. After loading the boundary conditions and numerical calculations, the comparison results of measured values and simulated values were obtained, as shown in table 3.

### Table 3. Comparison of measured values and simulated values

| B.H.   | H /m | Measured value/Simulated value | B.H.   | H /m | Measured value/Simulated value |
|--------|------|--------------------------------|--------|------|--------------------------------|
|        | σH /MPa | σh /MPa | αH /º |        | σH /MPa | σh /MPa | αH /º |
| ZKC1   | 229   | 7.5 / 8.0 | 5.0 / 4.9 | 15 / 32 | ZKC2   | 260   | 13.4 / 9.8 | 8.1 / 7.0 | 78 / 68 |
|        | 248   | 8.0 / 8.7 | 5.1 / 5.4 | /       |        | 260   | 13.4 / 9.8 | 8.1 / 7.0 | 78 / 68 |
|        | 282   | 10.8 / 9.9 | 6.1 / 6.1 | 22 / 34 |        | 310   | 11.2 / 11.7 | 8.3 / 8.4 | /       |
|        | 301   | 11.2 / 10.6 | 7.0 / 6.5 | /       |        | 310   | 11.2 / 11.7 | 8.3 / 8.4 | /       |
|        | 319   | 11.8 / 11.2 | 6.8 / 6.9 | 34 / 35 |        | 310   | 11.2 / 11.7 | 8.3 / 8.4 | /       |
|        | 336   | 12.3 / 11.8 | 7.1 / 7.3 | /       |        | 310   | 11.2 / 11.7 | 8.3 / 8.4 | /       |
| ZKC13  | 244   | 7.5 / 8.6 | 4.3 / 5.3 | 328 / 315 |        | 331   | 9.9 / 10.7 | 5.8 / 6.3 | 294 / 311 |
|        | 250   | 8.2 / 8.8 | 4.8 / 5.4 | 332 / 315 |        | 331   | 9.9 / 10.7 | 5.8 / 6.3 | 294 / 311 |
|        | 262   | 8.3 / 9.2 | 4.7 / 5.7 | 313 / 317 |        | 389   | 10.4 / 12.6 | 6.9 / 7.4 | 309 / 310 |
|        | 269   | 8.4 / 9.4 | 5.1 / 5.8 | 356 / 320 |        | 389   | 10.4 / 12.6 | 6.9 / 7.4 | 309 / 310 |
|        | 277   | 9.5 / 9.7 | 5.5 / 6.0 | 320 / 322 |        | 435   | 12.2 / 14.1 | 8.3 / 8.2 | 298 / 314 |
|        | 440   | 14.3 / 14.3 | 9.5 / 8.3 | /       |        | 440   | 14.3 / 14.3 | 9.5 / 8.3 | /       |
| ZKC18  | 463   | 13.3 / 15.0 | 8.2 / 8.8 | /       |        | 463   | 13.3 / 15.0 | 8.2 / 8.8 | /       |

As shown in the table, the stress difference between the simulated stress and measured stress was in most cases less than 1 MPa, and the simulated stress direction tended to follow the measured stress direction. Therefore, the initial stress field of the project area obtained by multiple regression analysis is reasonable and reliable.

#### 4.1. Distribution law of the horizontal principal stress value

Owing to space limitations of this paper, only the horizontal principal stress nephogram of the headrace tunnel, powerhouse area, and tailrace tunnel is given, as shown in figures 5 and 6.
Combined with the gravity stress of overlying strata, the relationship between the three principal stresses is mainly $\sigma_H > \sigma_z > \sigma_h$. Figure 5 shows that the maximum horizontal principal stress of the tunnel was mainly in 10–20 MPa, which is at the medium stress level according to relevant standards of hydropower projects. Affected by the physical and mechanical parameters of rock mass, the stress value in the fault zones is obviously lower than that in the original rock. In the center of the fault zone, the stress value was lowest; with distance from the center, the stress value gradually increased to the original rock stress state. However, the in situ stress field of the shallow strata was disturbed by faults in a wider range. With an increase in strata depth, the stress difference between the original rock and the fault decreased gradually, which indicates that the fault’s influence on the stress field of the deep strata became smaller.

4.2. Distribution law of the maximum horizontal principal stress direction

As indicated by the measured stress values, obvious differences were present in the direction of maximum horizontal principal stress. To analyze the influencing factors, it is necessary to extract the homogenization interpolation data from the numerical simulation results. Then, according to the interpolation data, a distribution map of the maximum horizontal principal stress direction at elevations of 2,000 m, 1,300 m, and 800 m corresponding to the elevations of the headrace tunnel, powerhouse, and deep strata, respectively, can be drawn, as shown in figure 7.
Figure 7. Distribution map of maximum horizontal principal stress direction at different elevations

At the elevation of 2,000 m, the strata depth is less than 400 m in the study area. Owing to topography differences, some of the ground elevation are less than 2,000 m; these areas appear in the form of blank spaces in figure 7(a). Regarding the S–N oriented valley in the middle region as the boundary, the $\alpha_{H}$ values differed significantly between the sides. Affected by a NW-oriented mountain on the left side, the $\alpha_{H}$ is NW in the southern region of the surge shaft. In the northern region, however, $\alpha_{H}$ deflects with the change in topography and burial depth, gradually transitioning from NW to S–N and before finally stabilizing in the NNE direction. Affected by a NNE-oriented mountain and a few NEE-striking faults on the right side, the $\alpha_{H}$ is mainly in the NNE–NEE direction. In the vicinity of large-scale faults, such as the fault zone composed of F18-1 and F18-2, the stress field is greatly affected by the fault zone, resulting in $\alpha_{H}$ approximating the fault strike.

At the elevation of 1,300 m, the strata depth of the powerhouse and tailrace tunnel is still shallow. Thus, the $\alpha_{H}$ is in the NW direction, controlled by the NW-oriented mountain. In the northern area of the powerhouse and tailrace tunnel, the burial depth of the strata is almost below the elevation of the deep gully. The effect of topography on the stress field is reduced, thus, the $\alpha_{H}$ is mainly close to the direction of the regional tectonic principal compressive stress, which is shown as the NNE–NE direction. Compared with that at 2,000 m elevation, the fault disturbance effect on the stress direction is obviously smaller.

At the elevation of 800 m, the strata is deep enough for the effect of topography and fault on the stress direction to be negligible. Then, $\alpha_{H}$ in the entire study area tends to be the direction of the regional tectonic stress, i.e., NNE.

5. Conclusion

Based on the measured data and stress field regression inversion, this study examines the in situ stress distribution characteristics of Suki–Kinari hydropower station and further summarizes the stress distribution laws of typical topography and fault development areas. The main conclusions are summarized below.
(a) The measured stress differs significantly among the boreholes, which is related mainly to its local geological conditions. Generally, the relationship among the three principal stresses is $\sigma_H > \sigma_z > \sigma_h$, and the stress direction is not consistent owing to the differences in topography.

(b) In the fault zone, the stress value is obviously lower than that in the original rock. The value reaches its lowest in the center of the fault zone and gradually increases to the original rock stress state with distance from the center. However, the faults have a greater impact on the stress disturbance of shallow strata, and gradually decrease as the depth of the strata increases.

(c) The direction of the maximum horizontal principal stress of the shallow strata is affected mainly by topography and faults, of which the topography might be the most important factor. With an increase in the strata depth, the influence of topography and faults on the stress field gradually decreases, and the stress direction of deep strata tends to the direction of the regional tectonic stress.

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7. References

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