



Sensitivity Analysis of Local Geological Parameters in Slopes Based on Orthogonal Experiments

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Abstract. A sensitivity analysis was conducted on two local geological parameters of the tailrace outlet slope at a pumped storage hydropower station to evaluate their influence on local geological displacement and the overall extent of the plastic zone. The analysis aimed to identify the critical factors influencing the slope's stability under different loading conditions. The results indicate that for relatively gentle slopes, the most significant factor affecting displacement within a given stratum is the elastic modulus, which represents the material's stiffness and its resistance to deformation. In contrast, the extent of the plastic zone, which indicates areas undergoing permanent deformation, is primarily influenced by Poisson's ratio. This is followed by the internal friction angle and cohesion, which also contribute to the overall behavior of the slope but to a lesser extent. These findings highlight the importance of carefully considering these parameters when assessing slope stability in such projects.

Keywords: geological parameters; slope stability; orthogonal experiment; influencing factors; parameter sensitivity analysis

1 Introduction

In engineering design and construction, ensuring the stability of slopes is a critical aspect to guarantee the safe and sustainable operation of a project. The stability of slopes can be influenced by a wide range of factors, which must be carefully evaluated to prevent potential failures[1]. One of the most effective ways to assess slope stability is through numerical simulation methods, which offer detailed insights into how the slope will behave under various conditions[2]. However, the results of these simulations can vary significantly depending on the parameters chosen, emphasizing the importance of selecting the right values for an accurate assessment.

After confirming the overall stability of the slope, the focus typically shifts to analyzing the deformation behavior and the extent of the plastic zone in localized areas[3]. These zones are of particular concern during excavation and support activities, as they provide important criteria for understanding the limits within which the slope remains stable[4]. It is during this phase that engineers can identify areas of potential failure and

take appropriate measures to reinforce the slope or adjust construction methods to ensure safety.

Numerical simulation results are highly sensitive to a variety of parameters, and slight variations in input values can lead to different outcomes. Some of these parameters, such as the slope's morphology, the physical properties of the rock mass, and the fluctuating groundwater levels, are determined by geological and climatic conditions. These factors are often beyond the engineer's control, making them challenging to modify. On the other hand, there are parameters, such as seismic forces, rainfall, and human-induced factors, that can be influenced by engineering practices and environmental changes[5]. These parameters can have varying degrees of impact on slope stability and need to be carefully accounted for in the design process.

The key factors affecting slope stability include cohesion, internal friction angle, unit weight, groundwater level, seismic forces, slope height, slope ratio, slope design, and top load. Each of these factors plays a unique role in determining the overall behavior of the slope. For instance, cohesion refers to the attractive forces between particles in the soil or rock, which helps maintain the stability of the slope[6]. The internal friction angle, which indicates the resistance to sliding, and the unit weight, which represents the weight of the material, are equally important. Groundwater levels can alter the effective stress within the soil, and seismic forces can introduce dynamic loads that challenge the integrity of the slope.

In practical engineering applications, geotechnical reports often provide a range of selectable values for the physical parameters of each rock layer. These values are based on field tests, laboratory experiments, and geological assessments. However, during numerical simulations, extensive trial calculations are necessary to determine the most appropriate values for these parameters, as there is often considerable variability in geological conditions. Given this variability, it is essential to conduct sensitivity analyses during the simulation process. Sensitivity analysis allows engineers to assess how changes in input parameters affect the stability results, helping to identify the most critical factors that influence the slope's behavior. By performing this analysis, engineers can better understand the degree of uncertainty in their design and make more informed decisions to ensure the safety of the project.

2 Method

2.1 Orthogonal Experimental Method

Orthogonal experiment design and analysis methods are based on probability theory, mathematical statistics, and practical experience. These methods employ standardized orthogonal design tables to arrange experimental plans and analyze the results efficiently. The primary objective is to identify and assess the influence of various factors on the outcome of an experiment by strategically selecting representative factors for experimentation. By using a subset of experiments to replace the entire set, the number of trials required is significantly reduced, which leads to a more cost-effective and time-efficient approach while still achieving a comprehensive understanding of the experimental outcomes.

This approach not only saves time and resources but also ensures the generation of high-quality experimental data, as it accounts for the interaction between different factors and their individual effects on the results. The orthogonal design table can be employed for various types of experimental result analysis, including range analysis, regression analysis, variance analysis, and covariance analysis. Each of these techniques provides different insights into the data, helping to draw meaningful conclusions and make informed decisions.

In this experiment, variance analysis and range analysis were primarily used. Range analysis, which is more intuitive and easier to understand, helps in identifying the effect of each factor on the experimental results by comparing the range of values across different levels of the factors. However, while range analysis offers a straightforward approach, it cannot differentiate the sources of variation in the experimental results. To overcome this limitation, variance analysis was also employed. Variance analysis helps to determine whether the observed differences in the data are statistically significant and whether the factors considered have a real impact on the outcomes. By supplementing range analysis with variance analysis, a more comprehensive and reliable interpretation of the experimental data can be achieved.

2.2 Design overview and Geological Condition Analysis

The pumped-storage hydropower station is designed as a first-class large-scale project, with a total installed capacity of 1400 MW, making it a major infrastructure development aimed at enhancing energy storage and supply stability. The upper reservoir has a normal water level of 2333.0 m, an adjustable storage capacity of 6.89 million m³, and a total storage capacity of 7.11 million m³, providing significant storage volume for peak load shaving. The lower reservoir, located at a normal water level of 1749.0 m, has an adjustable storage capacity of 6.85 million m³ and a total storage capacity of 7.07 million m³. The difference in elevation between the upper and lower reservoirs allows for effective energy generation through water flow during the discharge phase and efficient energy storage during the charging phase.

Key permanent structures in the project include the reservoir dams, water conveyance system, underground power plant, surface switchyard, lower reservoir dam, and flood discharge structures. These are all designed as Class I buildings, indicating the highest level of structural integrity and safety standards due to their importance for the stability and operational reliability of the hydropower station. Secondary permanent structures, which support the operation but are less critical, are designed as Class III buildings, while temporary structures used during construction or for short-term purposes are classified as Class IV buildings. The seismic intensity in the area is rated at VIII, which indicates a relatively high seismic risk, necessitating robust design and reinforcement of the station's structures to withstand potential earthquakes.

The project area features relatively flat terrain, which is advantageous for construction and operational stability. Based on reference geological data, a two-dimensional cross-section from an excavated slope was selected for analysis, providing a clear representation of the slope's characteristics. The slope has a low angle of inclination, mak-

ing it less prone to failure under normal conditions, but still requiring careful consideration during construction and in the design of stability measures. In the following discussion, M1 represents the slope's alluvial fan gravel, which is an important factor in the stability analysis due to its influence on soil properties and behavior under load.

3 Experiment

3.1 Orthogonal Table Experimental Design

Orthogonal tables are classified into two types: *same-level orthogonal tables* and *mixed-level orthogonal tables*. In *same-level orthogonal tables*, all factors have the same number of levels, and the different levels of each factor appear the same number of times in the design table. In contrast, *mixed-level orthogonal tables* allow factors to have unequal levels, enabling multi-factor experiments with different levels for each factor.

In this experiment, numerical simulation was conducted on a two-dimensional slope, with a particular focus on the M1 and M2 strata during excavation construction. A *same-level orthogonal table* was employed to design the experiment, as shown in Table 1. The $L_{16}(4^4)$ orthogonal table was generated using computer software, and the corresponding factors and levels were incorporated into the design of the experiment. Here, "16" denotes the total number of experiments to be conducted, "L" refers to the orthogonal table, the "4" in the bottom-left corner indicates that four levels are used, and the "4" in the top-right corner signifies that four factors are considered. The four selected factors for the experiment were cohesion, internal friction angle, elastic modulus, and Poisson's ratio. For each factor, four levels were chosen for analysis, resulting in 16 experimental runs for each stratum.

A comparative analysis was performed between the two strata, and values were uniformly selected within the parameter ranges specified in the geological report for the experiment. The cohesion values for the M1 stratum ranged from 0.012 MPa to 0.024 MPa, the internal friction angle ranged from 18° to 24° , the elastic modulus ranged from 40 GPa to 130 GPa, and the Poisson's ratio ranged from 0.32 to 0.41. For the M2 stratum, the cohesion values ranged from 0.03 MPa to 0.045 MPa, the internal friction angle ranged from 22° to 31° , the elastic modulus ranged from 400 GPa to 700 GPa, and the Poisson's ratio ranged from 0.31 to 0.4.

This methodology allows for a systematic and efficient evaluation of the influence of multiple geological parameters on slope stability, providing valuable insights into how variations in material properties can affect the overall behavior of the slope during excavation and construction. By employing orthogonal experimental design, the experiment ensures comprehensive data collection while minimizing the number of trials, thus optimizing the experimental process and enhancing the reliability of the results.

3.2 Calculation and Analysis of Local Slope Displacement

When conducting the analysis of local slope displacement, only the effects of changes in the parameters of each individual stratum on the corresponding stratum displacement

are considered. This focused approach isolates the influence of geological parameter variations on the displacement behavior of each layer. On the other hand, when analyzing the extent of the plastic zone of the slope, both the changes in two geological parameters are taken into account to assess their collective impact on the overall plastic zone extent of the same slope. This broader analysis provides a more comprehensive understanding of how variations in multiple factors may affect the overall stability and deformation behavior of the slope as a whole.

To perform these analyses, the parameters for each scenario were input into the computational models. The orthogonal design tables used for the experiment, along with the resulting calculations, are presented in Tables 1 and 2. The orthogonal design approach allows for an efficient and systematic exploration of the various parameter combinations, ensuring that the effects of each factor are thoroughly evaluated without the need for an excessive number of trials. The results from these analyses provide valuable insights into the deformation characteristics and plastic zone development under different geological conditions, thereby contributing to the overall stability assessment and risk management of the slope.

Table 1. M1 orthogonal design table.

Test Factors	Cohesion c/MPa	Internal friction angle $\phi/ (^{\circ})$	Elastic modulus E/GPa	Poisson's ratio μ	X displacement	Y displacement	Plastic zone extent
1	0.024	24	130	0.32	0.095	0.32	237
2	0.024	22	100	0.35	0.104	0.34	213
3	0.024	20	70	0.38	0.104	0.34	206
4	0.024	18	40	0.41	0.134	0.38	192
5	0.02	24	100	0.38	0.095	0.32	207
6	0.02	22	130	0.41	0.085	0.285	201
7	0.02	20	40	0.32	0.162	0.475	283
8	0.02	18	70	0.35	0.114	0.36	276
9	0.016	24	70	0.41	0.105	0.32	206
10	0.016	22	40	0.38	0.143	0.425	213
11	0.016	20	130	0.35	0.095	0.32	281
12	0.016	18	100	0.32	0.104	0.34	312
13	0.012	24	40	0.35	0.152	0.45	243
14	0.012	22	70	0.32	0.124	0.38	310

15	0.012	20	100	0.41	0.095	0.3	227
16	0.012	18	130	0.38	0.095	0.3	287

Table 2. M2 orthogonal design table.

Test Factors	Cohesion c/MPa	Internal friction angle φ (°)	Elastic modulus E/GPa	Poisson's ratio μ	X displacement	Y displacement	Plastic zone extent
1	0.045	31	700	0.31	0.0715	0.26	265
2	0.045	28	600	0.34	0.0715	0.26	226
3	0.045	25	500	0.37	0.0665	0.26	205
4	0.045	22	400	0.4	0.065	0.26	187
5	0.04	31	600	0.37	0.0665	0.26	200
6	0.04	28	700	0.4	0.055	0.24	179
7	0.04	25	400	0.31	0.0845	0.3	318
8	0.04	22	500	0.34	0.0715	0.28	307
9	0.035	31	500	0.4	0.065	0.24	189
10	0.035	28	400	0.37	0.077	0.28	211
11	0.035	25	700	0.34	0.065	0.26	292
12	0.035	22	600	0.31	0.0715	0.26	352
13	0.03	31	400	0.34	0.084	0.3	220
14	0.03	28	500	0.31	0.078	0.28	314
15	0.03	25	600	0.4	0.055	0.24	190
16	0.03	22	700	0.37	0.04	0.24	286

3.3 Calculation Results and Finite Element Analysis

The two-factor experiments for the M1 and M2 strata were selected for computational analysis, and the resulting displacement contour maps are shown in Figures 1 and 2. The vertical displacement is distributed in layers under the influence of gravity. Near the right boundary, the vertical displacement is significantly influenced by the large area of soil layers on the right side, resulting in a larger variation compared to the left side. The maximum vertical displacement is located in the upper right corner of the slope. Similarly, the horizontal displacement is also affected by the large soil mass on the right side; however, due to boundary effects, the maximum horizontal displacement does not occur at the right boundary but instead is located slightly to the left of it.

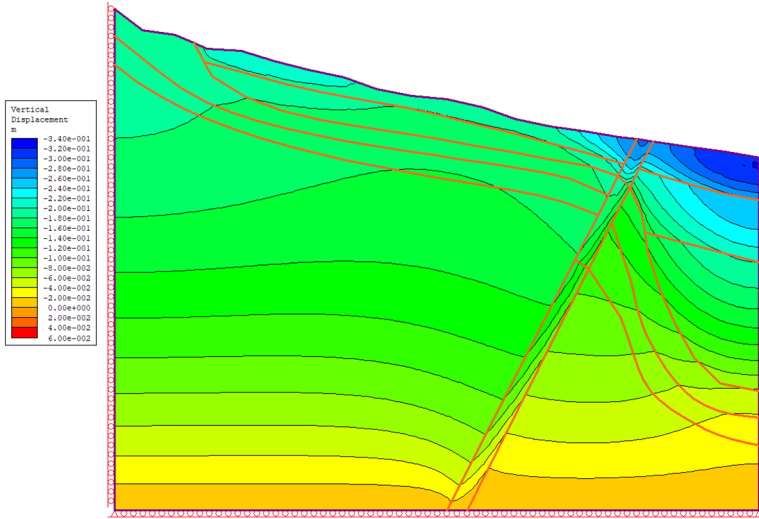


Fig. 1. Vertical displacement cloud map

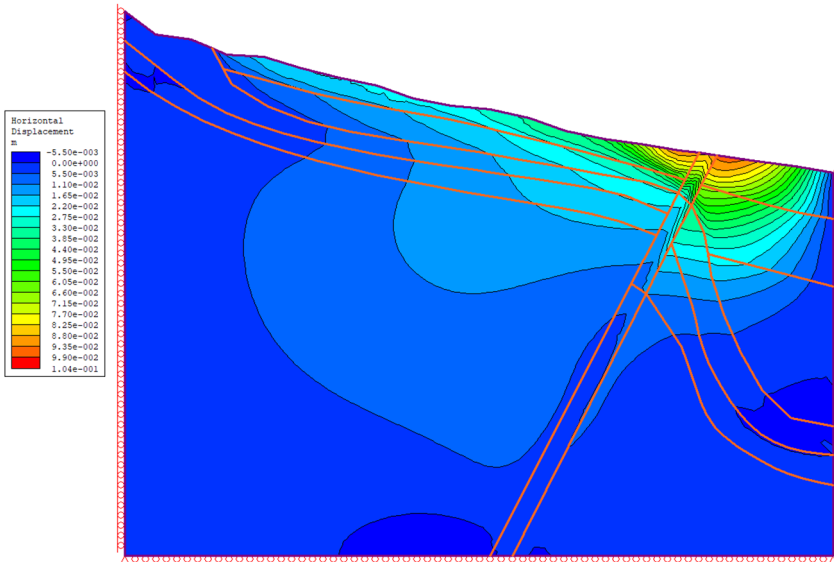


Fig. 2. Horizontal displacement cloud map

As shown in Figure 3, the elements experiencing tensile yield are primarily located in the upper right corner, where the displacement is more pronounced. Both the M1 and M2 strata exhibit similar trends in terms of displacement distribution, with relatively soft structural characteristics. The two strata are similarly influenced by different parameters, with their response to changes in these parameters being quite comparable. This indicates that despite the differences in material properties between the two layers,

their overall behavior under the given loading conditions follows similar patterns, and their responses to varying factors are close in magnitude.

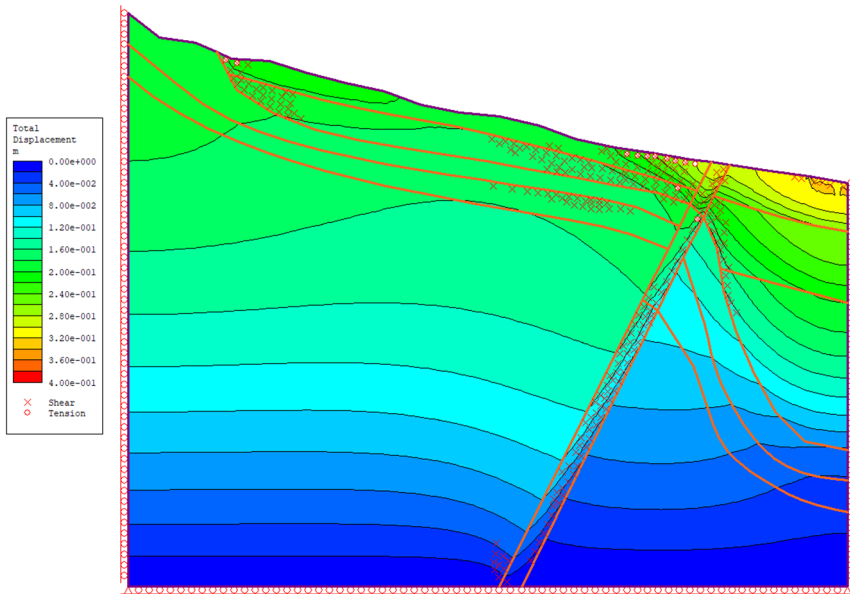


Fig. 3. Distribution diagram of yielding units

Within the specified parameter selection range, the sensitivity of the X-direction displacement, Y-direction displacement, plastic zone extent, and the number of yield cycles to different factors varies. In the post-processing contour maps, extreme values for both X-direction and Y-direction displacements consistently appear in the M1 and M2 strata. To analyze the displacement behavior of the two strata independently, the post-processing contour maps were analyzed such that the displacement extremes obtained after changing the parameters only correspond to the extreme values within the respective layer. When the extreme values appear in the corresponding stratum, they are directly displayed in the output contour map. However, when the extreme values are not observed in the corresponding stratum, the X-direction and Y-direction displacement extremes for that stratum are manually identified based on the different color gradients presented in the contour maps.

In order to account for the correlation between the two strata, the analysis of the plastic zone extent was conducted for the entire model, resulting in a comprehensive evaluation of the plastic zone across both strata. This approach provides a more holistic view of how the changes in parameters affect the entire model, rather than limiting the analysis to individual layers. The specific values for displacement and plastic zone extent across both strata are provided in Table 3. This method ensures that the interdependence of the strata is properly considered, thereby yielding a more accurate and integrated assessment of slope stability and deformation behavior under varying conditions.

Table 3. M1 range analysis results

Test Factors		Elastic modulus E/GPa	Cohesion c/MPa	Poisson's ratio μ	Internal friction angle $\phi/ (^{\circ})$
X displacement	k_{1j}	0.117	0.112	0.148	0.121
	k_{2j}	0.112	0.114	0.112	0.116
	k_{3j}	0.114	0.114	0.100	0.109
	k_{4j}	0.109	0.112	0.093	0.105
	R_j	0.008	0.002	0.055	0.016
Y displacement	k_{1j}	0.358	0.345	0.433	0.379
	k_{2j}	0.351	0.359	0.350	0.368
	k_{3j}	0.360	0.358	0.325	0.346
	k_{4j}	0.345	0.353	0.306	0.321
	R_j	0.015	0.014	0.126	0.058
Plastic zone extent	k_{1j}	266.80	266.80	232.80	285.50
	k_{2j}	253.00	249.30	249.50	253.30
	k_{3j}	241.80	234.30	239.80	228.30
	k_{4j}	212.00	223.30	251.50	206.50
	R_j	54.80	43.50	18.80	79.00

Where k_{ij} represents the average sum of the data corresponding to the i th level of the j th factor, and R_j denotes the range of values for each level under the j th factor

According to the range analysis results, for the M1 stratum, Poisson's ratio and elastic modulus have the greatest influence on local slope displacement, while the effects of internal friction angle and cohesion are relatively minor and exhibit similar magnitudes. Within the given parameter range, an analysis of displacement sensitivity reveals that the range values for X-direction and Y-direction displacement corresponding to Poisson's ratio are 0.055 and 0.126, respectively, whereas those for internal friction angle are 0.016 and 0.058. This indicates that Poisson's ratio and internal friction angle exert a significantly greater influence on displacement compared to elastic modulus and cohesion.

With respect to the plastic zone extent, Poisson's ratio demonstrates the highest sensitivity, followed by internal friction angle and cohesion, while elastic modulus exhibits the lowest sensitivity. The data is shown in Table 4.

Table 4. M2 range analysis results

Test Factors	Elastic modulus E/GPa	Cohesion c/MPa	Poisson's ratio μ	Internal friction angle $\phi/ (^{\circ})$
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X displacement	k_{1j}	0.064	0.062	0.078	0.076
	k_{2j}	0.070	0.068	0.070	0.073
	k_{3j}	0.069	0.070	0.066	0.063
	k_{4j}	0.069	0.072	0.058	0.060
	R_j	0.005	0.010	0.020	0.016
Y displacement	k_{1j}	0.265	0.260	0.285	0.275
	k_{2j}	0.260	0.265	0.265	0.275
	k_{3j}	0.270	0.265	0.255	0.260
	k_{4j}	0.260	0.265	0.250	0.245
	R_j	0.010	0.005	0.035	0.030
Plastic zone extent	k_{1j}	252.50	283.00	234.00	312.30
	k_{2j}	261.00	251.30	253.80	261.30
	k_{3j}	251.00	232.50	242.00	225.50
	k_{4j}	220.80	218.50	255.50	186.30
	R_j	40.30	64.50	21.50	126.00

For the M2 stratum, Poisson's ratio and elastic modulus have the greatest influence on local slope displacement, while internal friction angle and cohesion have lesser but comparable effects. Regarding plastic zone extent, internal friction angle is the most sensitive factor, followed by elastic modulus and cohesion, with Poisson's ratio having the least impact.

Comparing the M1 and M2 strata, Poisson's ratio and elastic modulus significantly affect slope displacement, while internal friction angle and cohesion have a smaller influence. The plastic zone extent is most sensitive to Poisson's ratio, followed by internal friction angle and cohesion, with elastic modulus having the least effect. Since range analysis cannot distinguish between factor influence and experimental error, variance analysis was conducted for accuracy.

Variance analysis confirms that elastic modulus most strongly affects local displacement, while Poisson's ratio has the greatest impact on the plastic zone, followed by internal friction angle and cohesion, with elastic modulus being the least influential. The results align with the range analysis findings, as shown in Tables 5 and 6 (**: highly significant; *: low significance).

Table 5. M1 ANOVA Results

Test Factors	Degrees of Freedom	F	Mean Square	Significance
Cohesion (c)	3	1.618	3.84E-5	*

X displacement	Friction angle	3	0.284	6.75E-6	*
	Elastic modulus	3	101.702	2.41E-3	**
	Poisson's ratio	3	9.021	2.14 E-4	*
	Error	3			—
Y displacement	Cohesion (c)	3	3.017	1.81 E-4	*
	Friction angle	3	2.600	1.56 E-4	*
	Elastic modulus	3	206.983	1.23 E-2	**
	Poisson's ratio	3	42.878	2.57 E-3	**
	Error	3			—
Plastic zone extent	Cohesion (c)	3	24.429	2168.083	**
	Friction angle	3	16.063	1425.583	**
	Elastic modulus	3	3.449	306.0833	*
	Poisson's ratio	3	51.990	4614.083	**
	Error	3	1.618	3.84E-5	—

Table 6. M2 ANOVA Results

Test Factors		Degrees of Freedom	F	Mean Square	Significance
X displacement	Cohesion (c)	3	1.884	2.53E-5	*
	Friction angle	3	5.535	7.43E-5	*
	Elastic modulus	3	20.223	2.72 E-4	**
	Poisson's ratio	3	18.799	2.53 E-4	**
	Error	3			—
Y displacement	Cohesion (c)	3	3.667	9.17E-5	*
	Friction angle	3	1.000	2.5E-5	*
	Elastic modulus	3	38.333	9.58 E-4	**
	Poisson's ratio	3	33.000	8.25 E-4	**
	Error	3			—
Plastic zone extent	Cohesion (c)	3	6.745	1239.229	*
	Friction angle	3	16.943	3112.896	**
	Elastic modulus	3	2.249	413.2292	*
	Poisson's ratio	3	62.495	11482.06	**
	Error	3	1.884	2.53E-5	—

4 Conclusion

(1) This paper analyzes the two-dimensional cross-section of the tailrace slope at a hydropower station. The orthogonal experimental method is employed to reduce the number of trials while ensuring high-quality data, demonstrating significant advantages in experimental design.

(2) Two strata of the engineering example are analyzed. When analyzing displacement, only the influence of individual stratum parameters on the respective strata is considered, while the plastic zone analysis takes into account the entire slope. The results show that the influence of parameters on displacement and the plastic zone differs.

(3) For slopes with a gentle gradient, elastic modulus significantly affects displacement but has a minimal impact on the plastic zone. Poisson's ratio has a significant influence on both displacement and the plastic zone. Cohesion and internal friction angle have a negligible impact on displacement but exert a noticeable effect on the plastic zone.

However, the study has some limitations. For instance, the analysis focuses only on two strata, which may not fully capture the complex geological conditions of other real-world cases with multiple layers and varying material properties. Additionally, the study uses a two-dimensional cross-section, which simplifies the three-dimensional nature of slope stability. Future research could consider three-dimensional modeling for a more detailed and accurate analysis of slope behavior. Moreover, the influence of dynamic factors, such as seismic activity and fluctuating water levels, has not been thoroughly explored and could be included in future studies to better simulate real-world conditions.

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