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Stability Analysis of Stilling Basin Slope on the Left Bank of Kala Hydropower Station

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Abstract. A stable slope is a crucial factor for water reservoir in a hydropower station regarding power generation. This paper mainly uses FLAC^{3D} to analyze the slope stability and excavation with reinforcement support of stilling basin on the left bank of Kala Hydropower station regarding different operation cases. The numerical analysis reveals that the slope stability meets the design specification of class A and II slopes, while the potential instability area is mainly located in fragmented structural rock mass and class IV rock mass. After the excavation and reinforcement, the stability of the slope is improved to a certain extent, and Sericitolited Sand Slate is located at the foot of the slope, which basically has no effect on the slope stability. The slope unloading and toppling deformation of the left bank regarding the engineering area is obvious, and the shallow surface rock mass is prone to relaxation and damage during the slope excavation process. Therefore, it is recommended that the support should be on time, and according to the geological situation revealed, appropriate reinforcement treatment can be taken to ensure the safety and stability of the construction period. Sericitolited Sand Slate has a certain range of exposure during the excavation process, resulting in slightly higher slope deformation, so it should be carefully excavated. The slate is easy to soften when exposed to water, so attention should be paid to the timeliness and effectiveness of drainage measures during the construction period to avoid local collapse damage caused by softening of rock mass.

Keywords. Slope stability, strength reduction method, numerical simulation

1. Introduction

The slope stability is always of great importance during the construction of different types of industrial or engineering buildings. In particular, a stable slope is a crucial factor for water reservoir in a hydropower station regarding power generation. The climatic, geological, and geomorphological are influencing factors for the failure of a slope, especially heavy rain, seismicity, and human activity [1]. A lot of software like FLAC^{3D}, Midas and Abaqus have been used for analyzing the slope stability. Also, stability of large hydropower generation system is always of great importance [2]. Huang (2019) has applied 3DEC to study the stability of a reservoir slope in Zhouning pumped storage power station, and mentioned that it could be important to implement support

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reinforcement during excavation [3]. Pan (2021) has proposed that heavy rain could be a dominant factor for the stability of a slope [4]. Also, Liang et al. (2015) have proposed that a slope failure during earthquake tends to occur when a cumulative plastic deformation exceeds a certain critical value, which means earthquake would influence the slope stability to some extent [5].

Kala Hydropower Station is located in Muli Tibetan Autonomous County, Liangshan Yi Autonomous area, Sichuan Province. It is the seventh hydropower station in the hydropower development planning of the Lianghekou to Kala River section of the middle reaches of the Yalong River.

2. Engineering Background

2.1. Basic Geology

The stilling basin slope on the left bank of Kala is steep and from the toe of slope to 100 m above is covered by fractured rock, while the bedrock is almost exposed. The toppling deformation of the surface is obvious. Affected by rainwater erosion or other factors, local part of the slope collapses and forms dangerous rock mass. Sericitolited Sand Slate developed under the toe of the slope, which is 20 m-75 m wide. Its maximum projection area is about 5260 m^2 and the overall extension direction is N1.3°E. The rock mass is soft and easy to soften when exposed to water. The distribution shape is shown on the right side of Figure 1. This is also a complex engineering problem while dealing with slope stability.

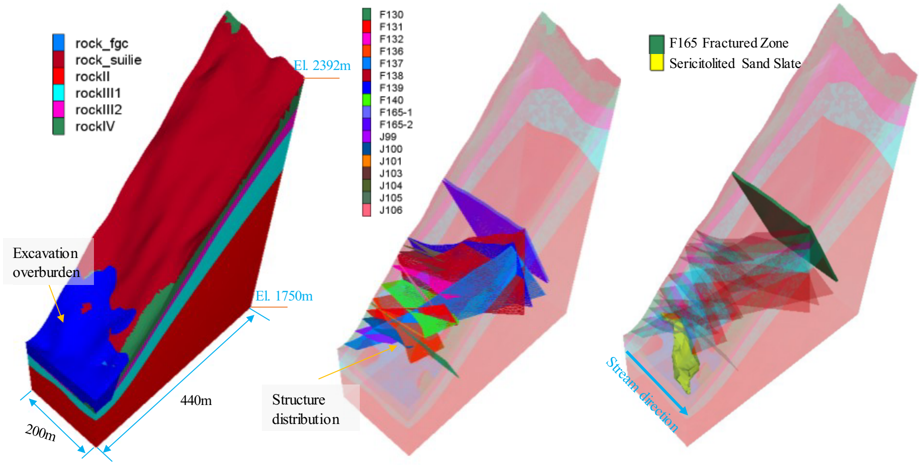

Figure 1. Numerical model of the slope and structures in FLAC^{3D}.

2.2. Standard of Design and FOS

According to the Code for Slope Design of Hydropower Projects (NB/T 10512-2021) [6], slopes should be divided into slope categories and safety levels according to the level of the hub project to which they belong, the level of the building, the location of the slope, the importance of the slope and the degree of hazard after the crash, and then determine the corresponding design safety factor.

The Kala hydropower station project is categorized as second-class large II, and the main buildings such as water retaining, flood discharge and water diversion are designed according to the level 2 buildings. The design parameter of the stilling basin slope on the left bank of Kala is shown in Table 1.

Table 1. Design parameters of the stilling basin slope.

Slope location	Classification	Design operation case		
		Normal	Saturated	Earthquake
Stilling basin slope	A type II class	1.20	1.10	1.05

2.3. Strength Reduction Method

In recent years, the strength reduction method has been widely applied to slope stability analysis, and the basic idea is to gradually reduce the strength parameters of rock and soil (mainly cohesion and the friction angle) in the process of slope calculation, and iteratively calculate until the slope reaches a critical failure state, at which time the ratio of the strength is the slope safety factor (FOS) [7-9]. The criteria for assessing slope instability typically encompass several factors, such as iterative solution convergence, penetration of generalized shear strain, distribution range and connectivity of plastic zones, and variation in displacement curves at critical points along the slope. Based on previous slope analyses conducted by ITASCA and drawing from relevant experiences and research findings, this study utilizes the convergence calculation criteria as well as the assessment of abrupt displacements at specific feature points. [10].

3. Numerical Analysis

3.1. Numerical Model

The numerical model and the distribution of structures are shown in Figure 1. The model range is 200 m × 440 m ($x \times y$, and x-axis is stream direction), while the bottom elevation of the model is 1750 m, and the top elevation is 2392 m. The model is composed of tetrahedral mesh division, and the number of elements is about 1.37 million, and the mesh in the key parts is refined, such as Sericitolited Sand Slate.

Empirically, structures in rock mass generally play a controlling role in the deformation mechanism and stability of the rock slope, so the structural surface with long extension, poor physical performance and great influence revealed in reality is directly simulated in the numerical model.

According to the classification of rock mass quality in the detailed design stage, the physical parameters of various rock masses and main structural surfaces are shown in Tables 2 and 3, and the Mohr-Coulomb (M-C) model is used for the calculation of the rock mass constitutive model.

Table 2. Material parameters of rock masses.

Material	**Young's passion ratio**		**Cohesion *C'(MPa)***		**Friction factor *f***		**Weight *(kN/m³)***	
	GPa	*v*	Natural	Saturated	Natural	Saturated	Natural	Saturated
Rock II	21.5	0.19	1.76	1.35	1.45	1.15	27.6	27.8
Rock III[1]	13	0.23	1.45	1.15	1.15	0.95	27.5	27.7
Rock III[2]	5	0.25	1.10	0.95	1.05	0.85	27.4	27.6
Rock IV	2.25	0.30	0.45	0.43	0.75	0.65	26.5	26.7
Rock Suilie (fractured)	2	0.30	0.425	0.4	0.625	0.56	26.5	26.7
Rock fgc (overburden)	0.1	0.45	0.075	0.065	0.625	0.60	20	22
Sericitolited Sand Slate	0.05	0.35	0.2		0.5		19.4	

Table 3. Material parameters of structures.

Fracture	**Cohesion *C'(MPa)***		**Friction Factor *f***	
	Natural	Saturated	Natural	Saturated
F130, F131, F132, F136, F137, F138, F139, F140, J99, J101, J103, J104, J105	0.12	0.10	0.50	0.45
F165, F139, F140, F100, F106	0.10	0.08	0.45	0.40

3.2. Constitutive Model and Material Parameters

The Mohr-Coulomb model is selected for the slope simulation. In the model, the used failure criterion is tension cutoff, and the failure envelope is illustrated in equations (1)-(3) [10].

$$f^s = -\sigma 1 + \sigma 3 N_\phi - 2c\sqrt{N_\phi} \tag{1}$$

$$N_\phi = \frac{1+\sin(\phi)}{1-\sin(\phi)} \tag{2}$$

$$f^t = \sigma_3 - \sigma^t \tag{3}$$

where, ϕ is the friction angle, c is the cohesion, σ^t is the tensile strength.

3.3. Slope Response after Excavation and Support

The slope response and cable stress after excavation and support are shown in Figure 2. Following excavation and reinforcement, the overall deformation of the slope in the stilling basin ranges from 6 mm to 10 mm. However, in the vicinity of the exposed Sericitolited Sand Slate, the maximum deformation reaches 16 mm to 18 mm due to the influence of unloading cracks along the slope. This poses a potential risk of relaxation and failure within the shallow rock mass. It is advisable to implement suitable reinforcement measures based on the specific construction conditions to address this issue.

The pre-tensioned anchor cable in design is simulated by the structural elements in $FLAC^{3D}$, and the calculation shows that the axial force of the cable is 1770 kN-1850 kN, which does not exceed its design load, compared with the pre-stressed load (90% in the calculation), only slightly increased. Therefore, it is recommended that the cable in the area of the stilling basin can be pre-tensioned according to 90%-100% of the design load.

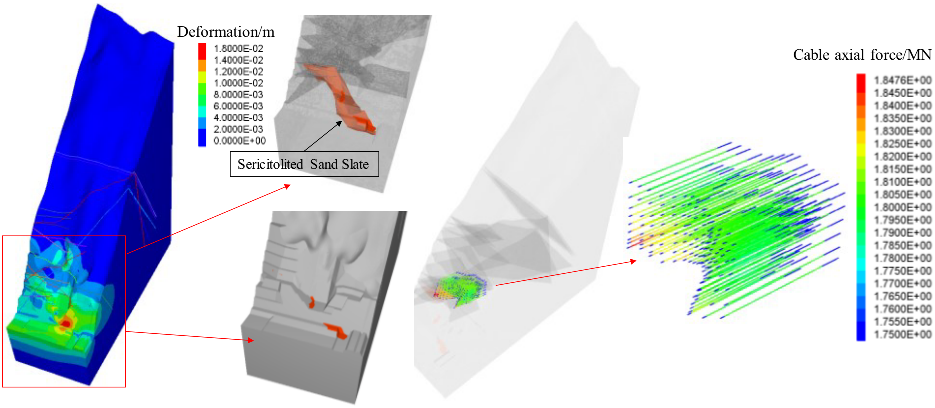

Figure 2. Slope deformation and cable stress after excavation and support.

3.4. Slope Stability Analysis

Figure 3 shows the deformation of key points of the slope to different FOS, after excavation and support reinforcement. Figures 4 and 5 show the potential deformation and failure characteristics of the slope of the stilling basin slope on the left bank under different operation conditions. As shown in Table 4, The stability analysis of the slope shows that under the normal, saturated and earthquake operation conditions, the safety of factor regarding the slope on the left is 1.32, 1.27 and 1.26, respectively, which can meet the design requirement. From the perspective of deformation characteristics, the area with large deformation of the rock mass on the slope after excavation support is not much different from the excavated unsupported slope, that is, mainly concentrated in the elevation above the slope excavation line of the stilling basin, but the safety factor of the slope is improved by the pre-tensioned anchor cable support. The calculation shows that the potential failure slipping zone mainly exists in slope fracture rock mass and class IV rock mass. The system support basically does not affect the deformation of the Sericitolited Sand Slate at the sliding surface and the toe of the slope.

According to the current excavation and support reinforcement plan, the stability of the slope is improved to a certain extent, and Sericitolited Sand Slate is located at the foot of the slope, which basically has no effect on the slope stability.

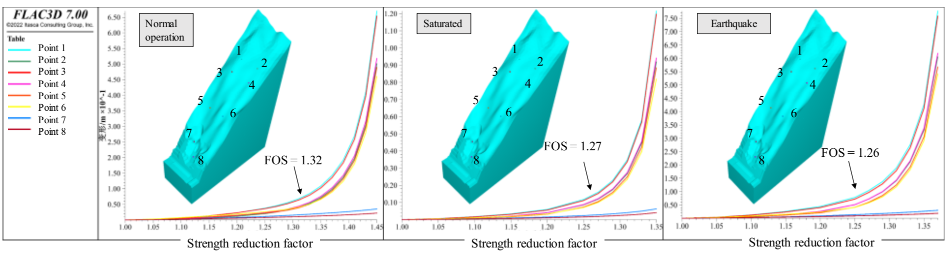

Figure 3. FOS of the slope under three different operation cases.

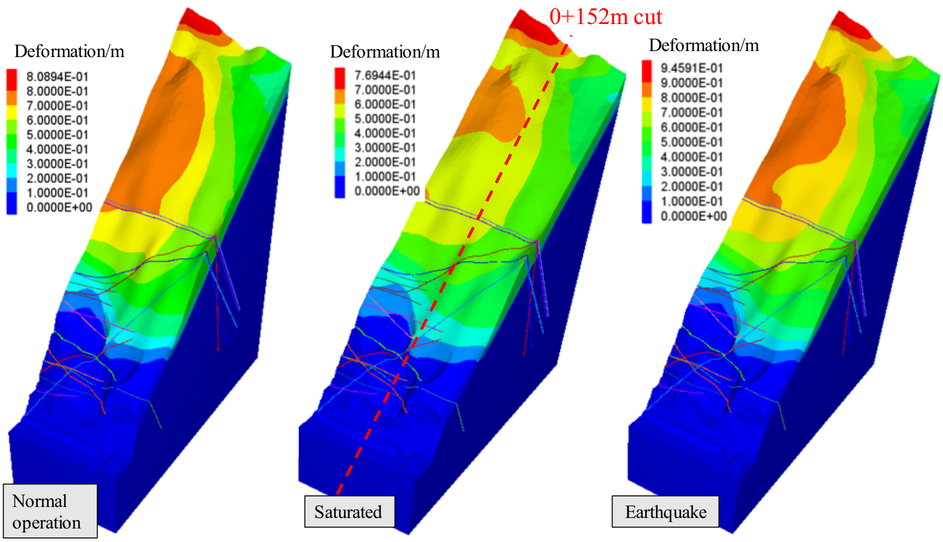

Figure 4. The deformation of the overall slope in different operation cases.

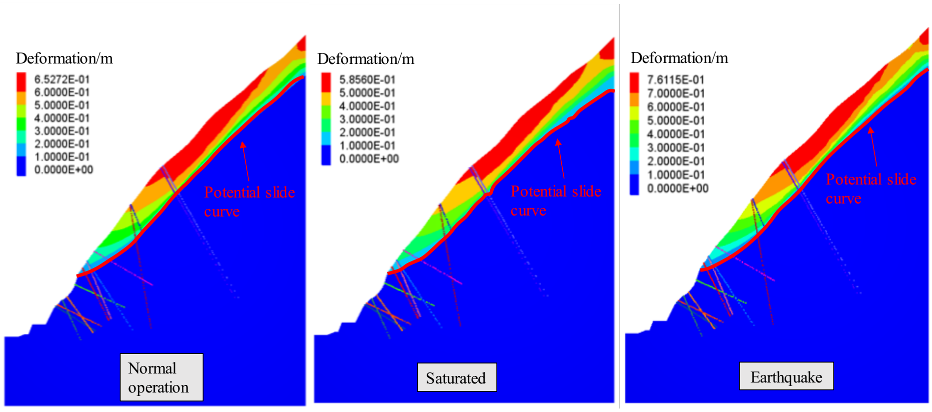

Figure 5. The deformation of 0+152 m cut of the slope in different operation cases.

Table 4. FOS of the stilling basin slope.

Calculation Condition	Natural Slope	Support Reinforcement	Design Standard	Acceptable
Normal operation	1.30	1.32	1.20	√
Saturated condition	1.24	1.27	1.10	√
Earthquake condition	1.25	1.26	1.05	√

4. Conclusions and Suggestions

This study utilizes FLAC^{3D} to analyze the stability and reinforcement of the slope of the stilling basin on the left bank of the Kala Hydropower Station. The main findings are as follows: (1) Numerical analysis shows that the slope stability meets the design specifications for Class A and II slopes under three different operational scenarios. The potential instability is mainly observed in fragmented structural rock masses and Class IV rock masses. (2) After excavation and reinforcement, the cumulative deformation of the stilling basin slope ranges from 6 mm to 10 mm. Near the exposed Sericitolited Sand Slate, influenced by unloading cracks along the slope, the maximum deformation reaches 16 mm to 18 mm. (3) The stability of the slope is improved to some extent through systematic reinforcement, and the presence of Sericitolited Sand Slate at the foot of the slope has minimal impact on slope stability.

Based on these results, the following suggestions are provided: (1) Due to obvious unloading and toppling deformation of the left bank slope in the engineering area, surface rock masses tend to relax and undergo damage during slope excavation. Therefore, it is recommended to implement timely support measures and employ appropriate reinforcement techniques based on geological conditions to ensure safety and stability during construction. (2) Careful excavation should be exercised since Sericitolited Sand Slate is exposed during the excavation process, resulting in slightly increased slope deformation. (3) As Sericitolited Sand Slate can soften upon water exposure, effective drainage measures should be implemented during construction to prevent local collapse caused by rock mass softening.

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