3D numerical modelling of stability of underground pumped storage hydropower (UPSH)

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ABSTRACT: In light of constructing larger and deeper underground pumped storage hydropower (UPSH) plants in deep valleys, a comprehensive study assesses their stability. Internal and external factors are analyzed for a typical underground hydropower station. Evaluating different rock mass types and mechanical qualities internally, the study also examines various station depths, major horizontal stress ratio (K), station angle α, and station length. It is found that increasing station depth and size amplifies stress and deformation of surrounding rock, but rock types with higher compressive strength display better resistance against excavation-induced stress and deformation. Notably, the station walls are more stable when station long axis aligns with the major horizontal stress σ_H, but it is expected to be less favorable for station end-wall and tunnels connecting caverns. It is crucial to consider rock properties, in-situ stress, and other key aspects for proper engineering measures for the deeper and larger UPSH plants.

Keywords: Stability analysis of underground pumped storage hydropower (UPSH), in-situ stress, rock type and quality, cavern length.

1 INTRODUCTION

In line with the United Nations Goal 7, hydropower holds significant importance as a clean energy priority in the global energy development market. Snowy 2.0, the largest renewable energy project in Australia, proposes a 750m deep underground pumped storage hydropower (Gomes et al. 2021); the Tauernmoos pumped storage plant, as part of Austria's 100% green energy 2023 target, is the height of a twelve-story house at a depth of 1500-2250m in Salzburg's Stubachtal valley (Herzog et al. 2022). The demand for larger and deeper UPSH plants is on the rise. Given the limited surface space and the advantages of utilizing the head difference, the construction of hydropower plants in deep valleys is prevalent. The stability of such UPSH plants depends on various internal and external factors, such as the mechanical properties of rock and rock mass, the presence of joints and fractures, deformation caused by excavation-induced constraint release, as well as high in-situ stress exposed on the plants, especially in deep valleys. The high stress and excavation-induced stress redistribution can contribute to post-peak behavior and induce squeezing phenomena in the surrounding rock, while the progressive deformation in the rock poses significant risks to the stability of underground stations.

Researchers have conducted many investigations on the stability of underground hydropower plants. Some scholars researched stability analysis of underground projects by finite element method, DDA, and discrete element method (Yoshida & Horii 2004, Wang et al. 2005, Cai 2008, Zhang et al. 2014, Ma et al. 2020). Artificial intelligence technology, such as BPNN neural network (Goh & Zhang 2012), and microseismic (MS) monitoring (Li et al. 2023) have also been applied to underground cavern stability analysis. Tezuka and Seoka (2004), Ma et al. (2020), Rahimi et al. (2021) carried out comprehensive studies on the stability of surrounding rock mass in the large underground hydropower station by combining theoretical calculation, numerical analysis or field monitoring for design, construction and monitoring. Some parametric analyses on the underground cavern have also been carried out by numerical modelling or field monitoring method: cavern length and rock mass properties of jointed rock mass (Hibino 2001); rock deformation modulus, cavern overburden depths, cavern height and initial major horizontal stress ratio (Zhu et al. 2010).

While previous scholars have conducted the underground cavern stability analysis on important parameters, the increasing demand for deep and large UPSH plants, characterized by high in-situ stress, poses greater challenges to engineering construction. Therefore, the comprehensive parametric studies on large-scale geometry, in-situ stress field, and different geological and geotechnical conditions should be further investigated. This study involves the modelling of a representative underground hydropower plant, and a parametric stability analysis is conducted in various rock types and in-situ stress field. Additionally, different lengths of stations are also studied on the influences on the stations, aiming to provide design and construction support for future hydropower stations.

2 METHODOLOGY

A general-size underground hydropower station is taken as the base model in this study (Hibino 2001; Zhu et al. 2010; Xu et al. 2015; Gomes et al. 2021; Herzog et al. 2022). The model consists of a machine hall (30m W,68m H, 132m L) and a transformer hall (20m W, 40m H, 108m L), as shown in Figure 1 below. A parametric study on the station length is conducted at the end of this paper, with the machine hall length varying from 76m, 104m, 132m to 250m, and the corresponding transformer hall length varying from 52m, 80m, 108m to 226m.

According to the in-situ stress global data on worldwide underground projects by González & Hijazo (2008), the vertical stress σ_V can be taken as 0.027 times overburden depth (0.027H), while the ratio (K) of major horizontal stress σ_H to vertical stress σ_V mainly ranges from 0.5-2.5. High-stress conditions normally occur in deep underground environments, therefore, potential projects 100-1500m deep are simulated and associated with the corresponding possible K (0.5-2.5). Additionally, angle α (0-90°) between σ_H and the axis of the station is also analyzed as an important influence.

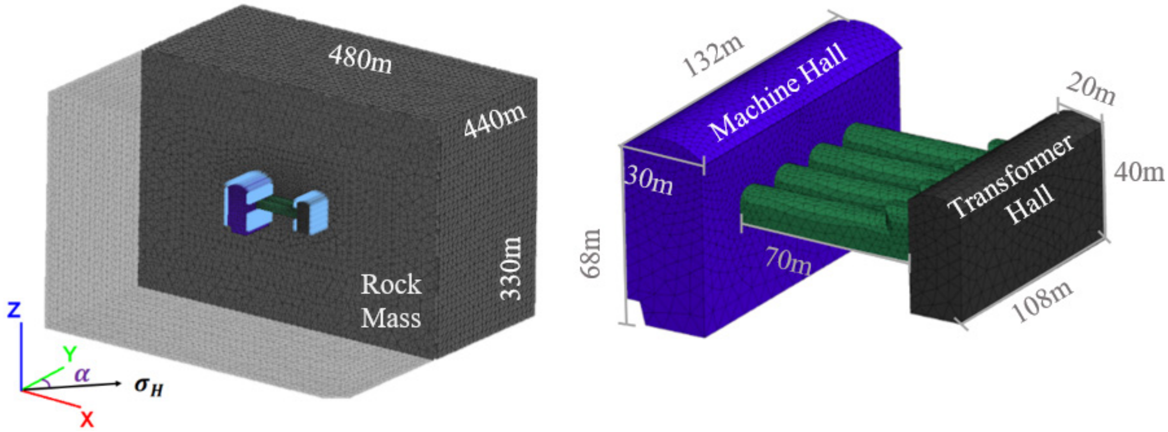

Figure 1. Model geometry of a general underground pumped storage hydropower station.

Based on the generalized Finite Difference Method (FDM), FLAC3D software is applied, and the resulting displacement is regarded as one of the indicators to reflect structure stability and mechanical behavior of surrounding rock mass. The isotropic and homogeneous rock mass is assumed, and the softening rock characteristics with Strain-Softening Mohr-Coulomb (SSoft) Model are employed to emphasis the potential for large deformation. Table 1 below shows the different rock types, and the key parameters of strain-softening rock mass are outlined.

Table 1. Geotechnical Parameters used in the numerical modelling.

Rock Type	Density (kg/m^3)	Deformation Modulus (GPa)	Poisson's Ratio	c_p/c_r (MPa)	ϕ_p/ϕ_r (°)	In-situ stress σ_1(MPa)/K
Marble (Feng et al. 2016)	2600	25.3	0.22	18.9/8.5	23.4/18*	-51.2/0.77
Sandstone (Hibino 2001)	2500	26	0.23*	6.3*/1.7*	39.5*/27.6*	-10.6/1.39
Granite (Xu et al. 2021)	2700	22.5	0.25	8/2	20/15.2*	-22.77/1.51
Basalt (Li et al. 2018)	2800	9.1	0.2	1.4/0.84*	52/46*	-11/1.38
Shale & Sandstone (Robert 2014)	2400	2	0.25	0.5/0.25*	50/43*	-5/2.0
Mudstone (Hibino 2001)	1700	0.8	0.21*	1.2*/0.62*	26*/18.2*	-1.17/0.99

*Typical values are taken based on projects

*c_p, c_r represents peak and residual cohesion; ϕ_p, ϕ_r represents peak and residual friction angle

*K represents major horizontal stress ratio, which is the ratio of major horizontal stress σ_H to vertical stress σ_V

Rock bolts and concrete lining are simulated and installed at one step behind the excavation with an excavation advancing rate of 3m/step. Typical rock bolts (8m in length, 2m of spacing) and concrete lining (0.6m in thickness and 15GPa of Young's modulus) are applied to the model, together with grouting and interface functions employed in the analysis.

3 RESULT AND DISCUSSION

3.1 Stability analysis of UPSH in in-situ stress field

Figure 2 shows the result of displacement on the station, where the machine hall is in 132m length and sits in the aforementioned Marble/Basalt rock type with 1.5K. From Figure 2, significant deformations are observed located on the sidewall of the machine hall as well as the tunnel connecting to caverns. Focusing on the station walls, displacement monitoring point A for following study is set on the sidewall of the machine hall which shows the maximum displacement of the machine hall itself in Figure 2. The stress monitoring point B is set on the top of concrete lining on the cavern arch. The deformation differences due to different rock types and mechanical qualities can also be observed.

The parametric study on in-situ stress field results in Figure 3 and Figure 4. From Figure 3, it is noticeable that, even though the displacement at monitoring point A on machine hall is affected by the angle α and the ratio of major horizontal stress σ_H to minor horizontal stress σ_h, the main station walls have a more stable behavior when the axis of the station is aligned with the major horizontal stress ($\alpha = 0$). In terms of stress magnitudes, high in-situ stresses normally appear in deep underground spaces, which makes the station exposed to more stress with larger deformation.

However, rock with higher compressive strength is more resistant to stress and deformation caused by excavation.

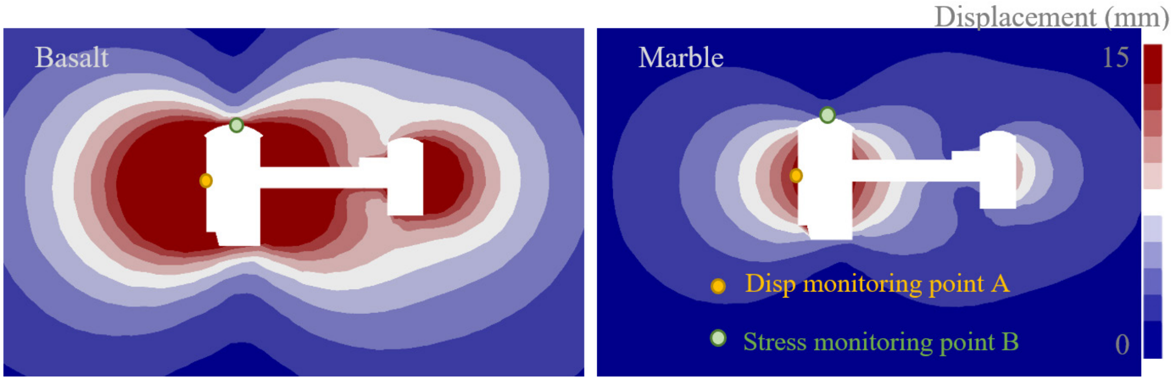

Figure 2. Numerical modelling result of displacement in 300m depth with K=1.5 in Basalt condition (left) and in Marble condition (right).

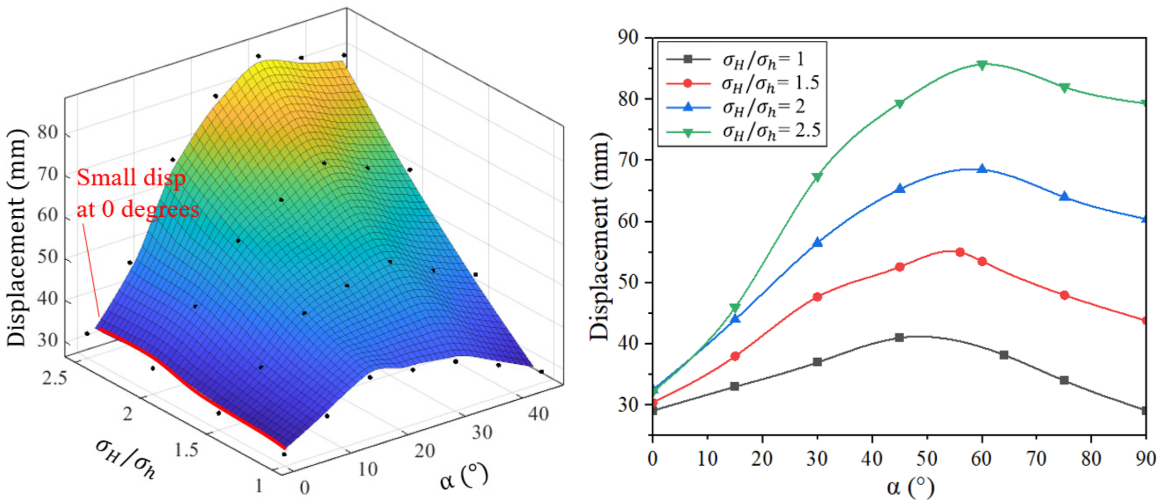

Figure 3. Displacement on the monitoring point A (machine hall in 132m L) at different angle α (the angle between axis of station and major horizontal stress) in 500m depth of Sandstone condition.

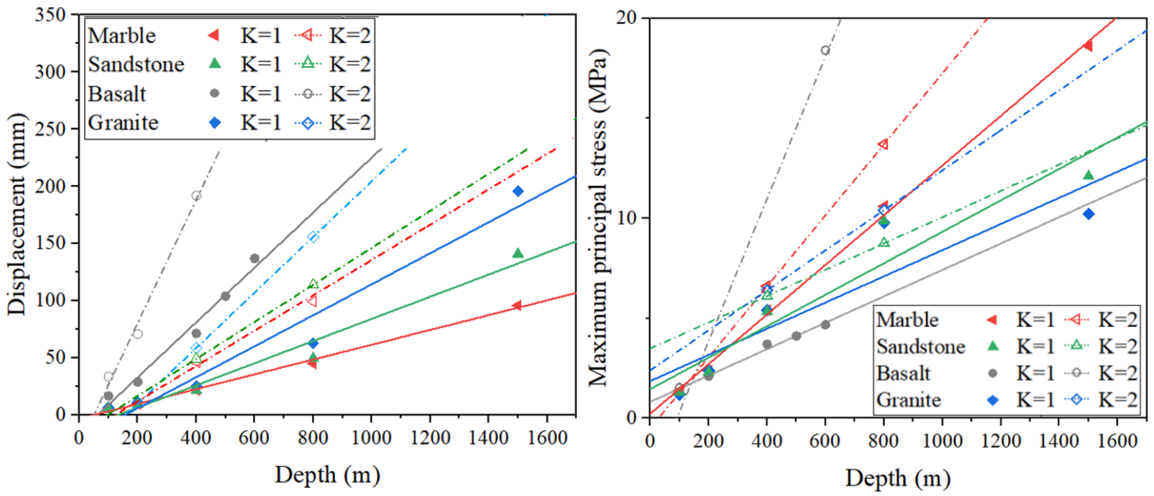

Figure 4. Displacement at point A (left) and maximum principal stress at point B on concrete lining (right) in different rocks with different K values (machine hall in 132m L).

3.2 *Stability analysis of UPSH in Cavern Length*

Figure 5 illustrates the relationship between the behavior of the hydropower station and different station lengths, under different depths and K values. It is observed that the monitoring displacement at point A and maximum principal stress at point B on the station have a nearly linear relationship with the station length respectively. The longer and larger the station, the greater the stress and the deformation that happens in the surrounding rock. In the meantime, rock type with mechanical quality is another crucial factor in deciding the stability of the station.

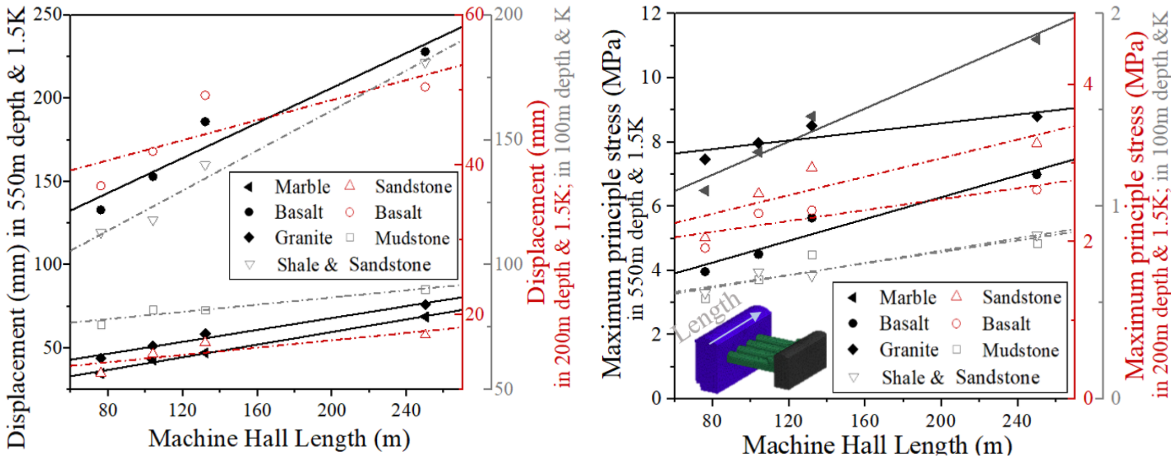

Figure 5. Relationship between displacement at point A and station length (left); Relationship between maximum principal stress at point B and station length (right).

4 CONCLUSION

The stability of hydropower stations has been analyzed under different rock types, in-situ stress fields, and cavern lengths. It is concluded that the main station walls have a generally better stability performance if it aligns with σ_H, however, the stability of station end-walls and tunnels connecting the caverns is expected to be less favorable. Moreover, high in-situ stress in deeper underground space exposes more pressure and causes greater deformation on stations, and rock with lower compressive strength and mechanical quality needs more attention and support due to a relatively low resisting capacity. In addition, the deformation and stress on the station have an almost linear relationship with the length of the station. The longer and larger the station, the greater the stress and the deformation of the surrounding rock. Therefore, a comprehensive design and careful support are required for large-scale UPSH plants. However, the study of fault zones in rock mass should be conducted as an important part of the comprehensive and systematic stability analysis of UPSH plants. Other critical criteria such as rock pillars and local wedges should also be analyzed on a case-by-case basis.

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