Numerical Simulation with FLAC^{3D} on Excavation Process of Underground Powerhouse of Kaluma Hydropower Station

An Liu, Hua Li, Fei Lu, and Meifeng Niu

Abstract The dam site of Kaluma Hydropower Station is located on the Nile River in northern Uganda. It is a diversion power station with a total installed capacity of 600 MW. The gneissic fissures and medium dip fissures in the plant area not only reduce the strength of the rock mass, but also easy to form adverse combinations and cuts, which adversely affecting the stability of the cavern. Therefore, surrounding rock deformation and block instability are the key factors affecting the stability of underground caverns. Based on the field investigation data, according to the research of geological prototypes such as rock mass structural plane investigation and quality classification, this paper uses the finite element numerical analysis software FLAC^{3D} to establish and calculate the numerical model, adjusts the boundary conditions of the model through parameter inversion, and then calculates the stress and strain of each part of the rock mass, so as to evaluate the excavation stability of underground powerhouse construction. The actual situation of construction and excavation verifies the accuracy of numerical analysis and calculation.

Keywords Underground powerhouse · Stability of surrounding rock mass · FLAC 3D

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1 Introduction

The dam site of Kaluma Hydropower Station is located on the Nile River in northern Uganda. It is a diversion power station with a total installed capacity of 600 MW, mainly composed of water retaining sluice dam, diversion system, underground powerhouse, tailrace tunnel and other buildings. The head sluice dam, with the maximum dam height of about 14 m and the normal pool level of 1030 m; The size of the plant is 200 m × 19.6/21.3 m × 53 m (length × wide × height).

Underground powerhouse cavern group mainly includes main (auxiliary) powerhouse, main transformer tunnel, tailrace surge chamber, tailrace adit, bus tunnel, outgoing shaft, construction adit and other caverns. Among them, the buried depth of the powerhouse, main transformer tunnel and tailrace surge chamber is about 69 ~ 140 m, and the axis orientation of the cavern is N39° W. The ground elevation of this area is about 1057 ~ 1062 m. Among them, the size of underground powerhouse is 200 m × 19.6/21.3 m × 53 m (length × wide × height), the top arch elevation is 971 m, and the floor elevation is 916 ~ 947.55 m.

The rock mass mechanical environment where the cavern is located is the basis for stability evaluation and support design, including geological environment (rock mass structural characteristics), mechanical environment (including rock mass stress field conditions and rock mass strength conditions), dynamic environment (including seismic geological environment and groundwater dynamic conditions). The stability analysis methods of surrounding rock of underground caverns can be roughly summarized as engineering geological analogy method, rock mass structure analysis method, rock mass stability mechanical analysis method and simulation test method [1]. The simulation test method includes physical simulation and numerical simulation. With the development of calculation technology and the wide use of computers, the numerical simulation method has obvious advantages in studying the development of stress, deformation and failure of surrounding rock of underground caverns, and then quantitatively evaluating the stability of surrounding rock. It has increasingly become the most powerful tool to solve the problems of underground engineering design and construction.

Therefore, based on solid and detailed field investigation data, this paper will analyze the mechanical environmental conditions of rock mass and their relationship, establish the constitutive model of rock mass, and adopt appropriate data processing technology and calculation methods to accurately evaluate the stability of underground powerhouse caverns.

2 Rock Mass Quality Classification

The stability of underground caverns is closely related to rock strength and discontinuous structural plane, of which the latter has a greater impact, that is, the rock mass shows strong anisotropy [2]. Due to the size effect, poor representativeness and many other adverse effects of indoor rock tests, rock mass classification systems have gradually developed [3]. Among them, RMR and Q systems are the most popular in the world, and suggestions for supporting support systems have been put forward respectively [4]. Generally, they are mainly considered: rock strength, rock mass structure, roughness of discontinuous structural planes, extensibility alteration degree, fillings, groundwater, in-situ stress conditions, excavation methods and other factors [5].

The surrounding rock classification of underground powerhouse area adopts Q system and RMR classification method for comprehensive evaluation. As the surrounding rock in the underground powerhouse area is mainly slightly weathered ~ fresh granite gneiss, the rock mass is hard and relatively complete, the structural plane is slightly ~ moderately developed, most of the caverns are dry, and there is only a small amount of seepage and dripping water locally, so it is mainly class II surrounding rock (RMR = 64 ~ 77, Q = 16 ~ 32), but the local tunnel section passing through the alteration zone is class III surrounding rock (RMR = 43 ~ 47, Q = 0.92).

3 Model of Underground Cavern Rock Mass

The boundary of the calculation area shall meet the requirements that the thickness of surrounding rock around the cavern is not less than 3 ~ 5 times the excavation diameter. The calculation area of Kaluma underground cavern group model includes the horizontal section of headrace tunnel, main power house, main transformer chamber, bus tunnel, ventilation shaft, tailrace tunnel, etc. The calculation range is 332 m × 440 m × 199 m, the coordinate origin is located at the bottom of the model. In the calculation model, the grid model of the underground cavern is shown in Fig. 1. The total number of discrete nodes is 119867, and the total number of elements is 709255.

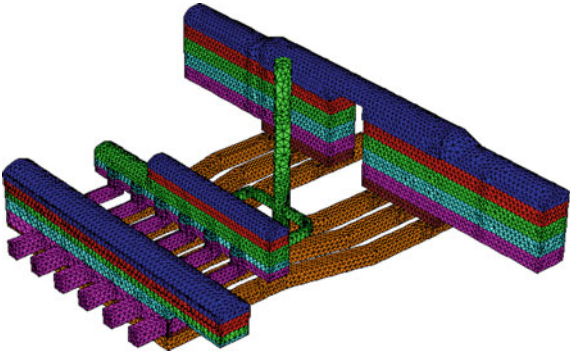


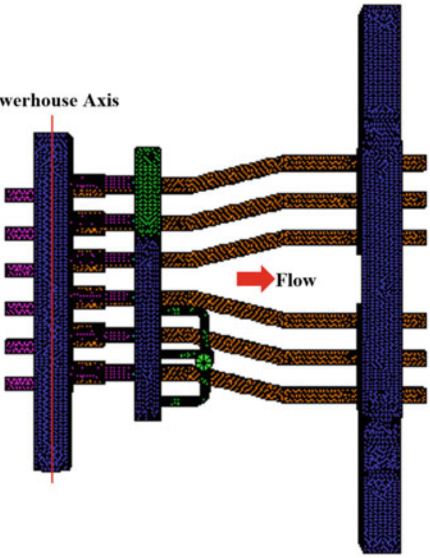
Fig. 1 Grid diagram of underground cavern

4 Results and Analysis

Through three-dimensional numerical simulation analysis, the construction process of the excavation of the cavern group is simulated, and the surrounding rock deformation field, stress field, plastic zone, etc. in order to reasonably evaluate the stability of the surrounding rock of the cavern group, combined with the engineering geological conditions and the structural form of the underground cavern group, the vertical section of the powerhouse axis is selected to analyze the calculation results after the excavation of the underground cavern. The specific location of the vertical section of the powerhouse axis is shown in Fig. 2.

After the excavation of the powerhouse, the maximum deformation of the surrounding rock of the section is mainly the rock wall between the end wall, the bottom plate boss and the machine nest, with the maximum deformation of 10 ~ 16 mm, the deformation of the end walls on both sides of 9 ~ 10 mm, and the deformation of the vault within the range of 4 ~ 5 mm (Fig. 3a). According to the stress analysis of the section, the maximum principal stress around the Powerhouse Tunnel is about − 10 ~ − 13 MPa, and the stress concentration of surrounding rock is not obvious (Fig. 3b); However, there is a certain stress relaxation. The minimum principal stress of surrounding rock at the vault and floor is about − 0.5 MPa, and there is no tensile stress in the rock around the tunnel (Fig. 3c); Compared with the displacement nephogram, the stress relaxation part is basically the same as the part with large deformation of surrounding rock, indicating that the deformation of surrounding rock in the section is mainly caused by the stress relaxation of surrounding rock after excavation. According to the plastic zone analysis of the section (Fig. 3d), the maximum plastic zone of the section is located in the rock wall between the bottom plate boss

Fig. 2 Schematic diagram of plant axis position



and the machine socket, and the maximum depth is 8 m; The depth of the plastic zone of the arch crown is about 2 ~ 3 m; The maximum depth of the plastic zone of the end walls on both sides is about 5 ~ 6 m.

It can be seen from the above that the deformation of the surrounding rock after the excavation of the power house is large, mainly the rebound deformation of the bottom plate boss and the rock wall between the machine sockets. There is a certain

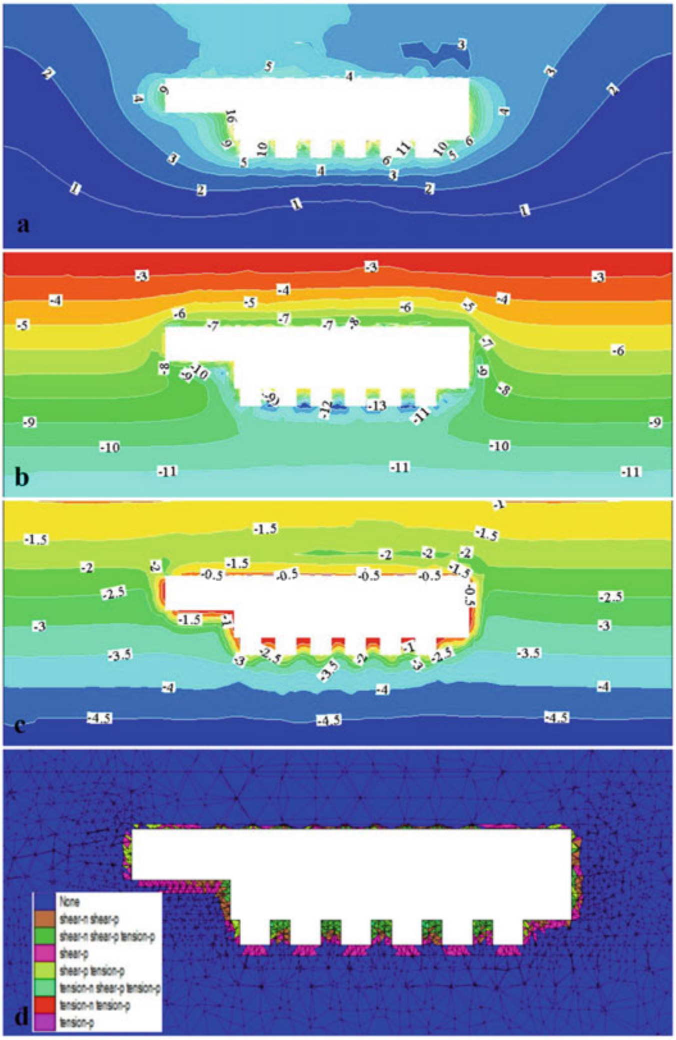


Fig. 3 Numerical simulation calculation results of surrounding rock of vertical section of plant axis after plant excavation: **a**-displacement (mm); **b**-maximum principal stress (MPa); **c**-minimum principal stress (MPa); **d**-plastic zone distribution

depth of plastic damage area on the vault of the power house. During the construction, attention should be paid to the removal of dangerous rocks, but the deformation and plastic area of the surrounding rock of the end walls on both sides of the power house, the bottom plate boss and the rock wall between the machine sockets are not small, so reinforcement and support should be considered.

After the excavation of the main power house is completed, the stress level of the crown is 7 ~ 8 MPa, the cumulative deformation of the crown is about 5 mm, the cumulative deformation of the upstream side wall of the main power house is about 15.6 mm, and the cumulative deformation of the downstream side wall is about 14.0 mm; The depth of the plastic zone of the crown is about 2 m, and the depth of the plastic zone of the side wall is generally 2 ~ 3 m; It can be seen that the stress value, deformation and plastic zone depth are very small, so the cavern is generally stable.

From the characteristics of surrounding rock deformation, plastic zone and secondary stress distribution, the powerhouse cavern group has good overall stability after excavation. It should be pointed out that the occurrence of plastic zone does not mean that the surrounding rock has obvious loosening. The in-situ stress characteristics and rock mass strength determine that the powerhouse tunnel group is mainly dominated by unloading relaxation and rebound deformation in the excavation process, and the stress adjustment generally will not lead to obvious loosening of the surrounding rock.

5 Conclusion

In this paper, the excavation process of underground powerhouse caverns is analyzed by using the finite element numerical analysis software FLAC^{3D}. The main conclusions are as follows:

In the buried area of underground powerhouse, the initial horizontal stress is greater than the vertical stress, so the stress concentration phenomenon appears in the top arch and bottom plate of Powerhouse after excavation. However, due to the small initial stress, the maximum value of secondary stress is generally about 10 MPa, which is far lower than the strength of rock mass, which is not enough to cause stress-induced failure of surrounding rock. During the excavation of underground caverns in the plant area of Kaluma Power Station, no obvious deformation damage and unstable block damage have occurred. Therefore, the actual situation of construction and excavation verifies the accuracy of numerical analysis and calculation.

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