Study on dynamic response characteristics of cave-type excavation of high and steep dam abutment slope

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ABSTRACT: The numerical simulation is carried out for the dynamic response characteristics of cave-type excavation at the left dam abutment of Zhongyu Hydropower Station. The results show that within the range of 20~100 m from the explosion source in the vertical direction, both the peak vibration velocity and the maximum principal stress of the particle present extremely obvious elevation amplification effect. Due to the influence of the ground stress and the excavation contour of the dam abutment, different layered blasting excavation and excavation unloading have different effects on the deformation and displacement of the surrounding rock of the dam abutment. In addition, during the excavation in a certain layer, the displacement change rate of the particles on the upstream and downstream sides of the dam abutment is usually first fast and then slow, and there will be obvious inflection points.

Keywords: high and steep dam abutment slope, cave-type excavation, blasting vibration, dynamic response, elevation amplification effect.

1 INTRODUCTION

The geological conditions in Southwest China area are quite complex and the ecological environment is extremely fragile, which poses great challenges to the stability and volume control of dam abutment excavation of hydropower projects (Song 2006). On the one hand, the natural slope in the alpine canyon zone is steep, the ground stress level is high, the rock mass unloading is strong, and the deep fractures are developed (Song 2010). On the other hand, as the height of the dam continues to refresh the record, the scale of the slope engineering is also increasing. The upper side of the excavation slope may even retain a natural slope of hundreds to thousands of meters (Song 2011). The hydropower engineering industry has carried out a lot of research work in dam abutment excavation methods, slope stability control, ecological environment protection in disturbed areas, etc. (Shen 2016). Chen et al. (2021) and Xia et al. (2020) and Chen et al. (2020) reduced the disturbance of blasting vibration on dam abutment slope by controlling blasting parameters and optimizing blasting technology. Zheng et al. (2020) and Xu et al. (2018) and Zheng et al. (2019) and Zheng et al. (2017) proposed new methods and new means for monitoring and controlling the stability of high and steep slopes. Chen et al. (2013) and Mu et al. (2020) and Auestad et al. (2018) conducted a lot of research and experiments on environmental protection and ecological restoration in the disturbed area, and put forward many new ideas.

At the same time, a "cave-type" layout and excavation construction method is recommended (Li 2011), which is different from the traditional open excavation method of dam abutment. As shown in Figure 1, the dam abutment cave-type excavation refers to the excavation of "cave-type" in the mountains on both banks bearing the load at the arch end of the arch dam. Its top elevation is slightly greater than the arch dam crest elevation, and the width of different elevations is slightly greater than the thickness of the arch dam, so the whole connection part of the dam and the mountain is arranged in the "cave" (Xu 2018). This kind of dam abutment excavation method can not only meet the requirements of arch dam foundation treatment and dam abutment slope stability, but also skillfully combine the arch dam body shape with the high and steep terrain on both sides, which can significantly reduce the the amount of excavation work and protect the vegetation on the mountain surface on both banks (Li 2018).

Figure 1. Cave-type excavation of dam abutment slope (Xu 2018).

In the process of cave-type excavation of dam abutment, the blasting vibration effect caused by blasting excavation can not be ignored (Lu 2012). Therefore, in practical engineering, the corresponding response mechanism of the dam abutment slope during blasting and whether this response will affect the safety and stability of the dam abutment slope during construction are the main issues to concern about. To solve this problem, it is necessary to analyze and study the dynamic response characteristics of the cave-type dam abutment under blasting excavation.

2 NUMERICAL MODEL AND BLASTING PARAMETERS

In order to obtain the initial stress field of the dam site area, it is necessary to first establish a three-dimensional numerical calculation model centered on the dam site area of Zhongyu Hydropower Station. The length along the longitudinal river direction is 2250m, and the positive direction of the x-axis is from upstream to downstream. The length along the transverse river direction is 1250m, the positive direction of the y-axis is from the right bank to the left bank. The bottom of the model extends to the sea level elevation, and the vertical upward direction is the positive direction of the z-axis. The left dam abutment adopts the cave-type excavation method. The excavation area of the dam abutment is divided into several excavation zones, and the grids of surrounding rocks in the excavation area and its vicinity are densified. The established three-dimensional model of the left dam abutment is shown in Figure 2. The design excavation height of the dam abutment groove is 268m, and the span of the dam abutment groove along the longitudinal river direction is 10~57m. The embedding depth of the dam abutment groove along the transverse river direction changes with the slope shape and slope elevation, and the embedding depth range is 16~38m.

The calculation domain is divided into three weathering degrees of rock mass according to the weathering boundary: weak upper weathering, weak lower weathering and slight weathering. The parameter selection of numerical simulation calculation is shown in Table 1. The peak value of blasting impact load of blast hole is $P_0 = 358.6\text{MPa}$, and the peak value of equivalent blasting impact load is $P_e = 8.07\text{MPa}$, and then the equivalent loading of blasting load is uniformly applied on the excavation boundary. Among them, the rise time of blasting load t_u is 2.3 ms, and the duration time of blasting impact load is $t_d + t_u = 17\text{ms}$.

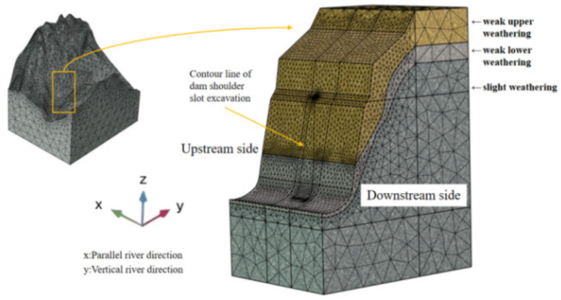


Figure 2. Three-dimensional model of the left dam abutment.

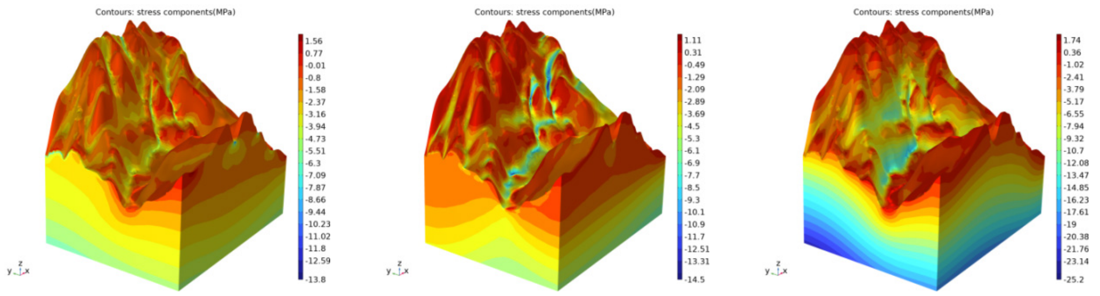
Table 1. Physical and mechanical parameters of rock mass.

Lithology	*E* (GPA)	*M*	*P* (KG/M^3)	*Σ* (MPA)	*C* (MPA)	*Φ* (°)
Slight weathering	27	0.23	2650	90	1.6	52.4
Weak lower weathering	18	0.26	2500	50	1	45
Weak upper weathering	14	0.28	2400	40	0.8	38.6

3 CALCULATION RESULTS AND ANALYSIS

3.1 Distribution characteristics of initial stress field

As can be seen from Figure 3, the distribution trend of stress vector in the dam site area is basically layered from top to bottom, the stress in the vertical direction gradually increases from the surface to the bottom and presents a linear distribution, and the variation law of stress with depth accords with the law of ground stress field in general river valleys. In addition, the stress at the design excavation of the dam abutment in the dam site area is about 11MPa, which is very close to the in-situ measured ground stress.



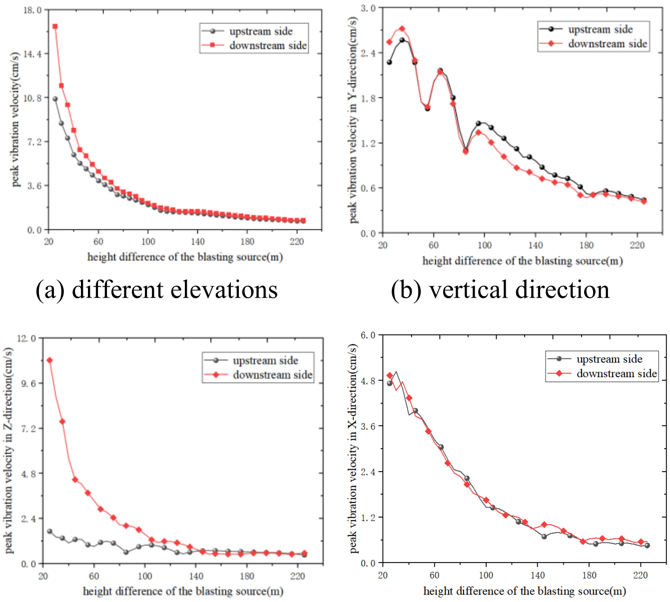
(a) X-directional (b) Y-directional (c) Z-directional

Figure 3. Contour map of stress distribution in the dam site area.

3.2 Attenuation law of blasting vibration velocity of dam abutment

The relationship between the peak vibration velocity of each monitoring point and the height difference of the blasting source is shown in Figure 4(a). It can be seen from the figure that with the increase of the height difference of the blasting source, the blasting peak vibration velocity on both sides of the dam abutment groove shows a gradual attenuation trend with distance. As can be seen from Figure. 4(b), the corresponding relationship between the peak blasting vibration velocity of the monitoring point in the vertical direction and the height difference of the blasting source. The peak blasting vibration velocity in the vertical direction on the upstream and downstream sides of the dam abutment groove presents a very obvious elevation amplification effect. For the upstream and downstream sides of the dam abutment groove, the elevation amplification effect of blasting vibration is mainly concentrated in the range of 20 ~ 100 m from the explosion source, and the amplification and attenuation trends of peak blasting vibration velocity in vertical direction are basically the same.

With the increase of blasting center distance, the local amplification effect of blasting vibration on both sides of the dam abutment groove decreases gradually.



(a) different elevations (b) vertical direction

(c) X direction (d) transverse river direction

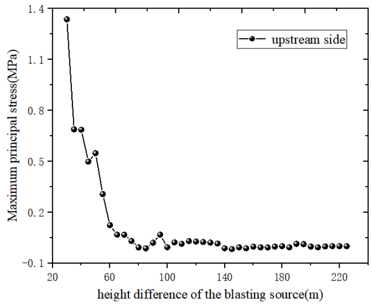
Figure 4. Variation curve of peak vibration velocity at different elevations

As can be seen from Figure. 4(c), the peak vibration velocities of the surrounding rocks on the upstream and downstream sides of the dam abutment groove are obviously different along the longitudinal river direction. The peak vibration velocity of the downstream side of the dam abutment groove along the longitudinal river direction (X direction) is obviously higher than that of the upstream side. The difference in the excavation overhang at the upstream and downstream sides significantly affects the propagation of blasting stress wave in the surrounding rock of the dam abutment groove. It can be seen from the Figure. 4(d) that there is no obvious difference in the overall attenuation trend of the peak vibration velocity along the transverse river direction on the upstream and downstream sides of the dam abutment groove, and a slight elevation amplification effect appears locally. The main difference between the upstream and downstream sides of the dam abutment groove in these aspects is the peak blasting vibration velocity along the longitudinal river direction. It can be seen that the different slopes of the upstream and downstream sides along the longitudinal river direction have caused this obvious difference.

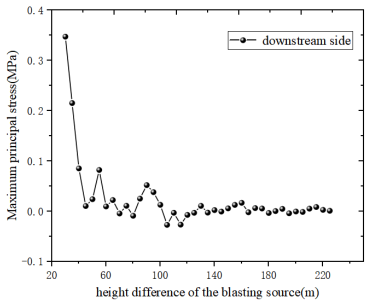
3.3 Relationship between blasting vibration velocity and stress state

According to the above analysis, there will be a certain amplification effect on both sides of the dam abutment groove. However, whether this amplification can truly represent the stress state in the slope and whether the speed of the amplification part can be used to evaluate the impact of the current blasting on the slope stability needs further verification. Compared with the peak vibration velocity (as shown in Figure. 5) in the vertical direction on the upstream and downstream sides of the dam abutment groove in the figure above, it can be found that there is a certain correlation between the peak vibration velocity of the particle and the position where the maximum principal stress appears.

Within the range of 20~100m from the explosion source in the vertical direction on both sides of the dam abutment groove, both the peak vibration velocity and the maximum principal stress of the particle in the vertical direction present extremely obvious elevation amplification effect. It can be seen that due to the impact of "whipping effect" of blasting vibration, the vibration velocity on the upstream and downstream sides of the dam abutment groove has a certain correlation with its stress state. Therefore, in the blasting vibration monitoring, the measuring points are arranged at the position with amplification effect and it has a certain reference value for evaluating the impact of the current blasting on the overall dam abutment groove.



(a) Upstream side

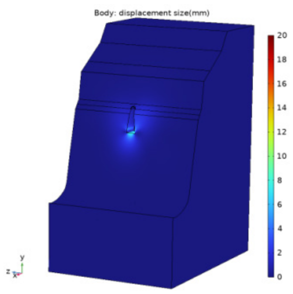


(b) Downstream side

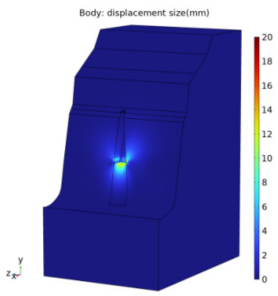
Figure 5. Maximum principal stress.

3.4 Displacement change of dam abutment slope under blasting excavation

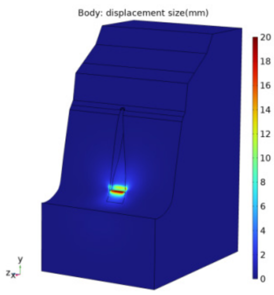
Figure. 6 shows the displacement nephograms of the left dam abutment slope during the 10th, 18th and 27th layers of blasting excavation. It can be seen from the figure that under the effect of blasting impact and excavation unloading, the displacement of the dam abutment slope increases significantly with the increase of excavation depth. The maximum displacements of the 10th layer, 18th layer and 27th layer are 7.5mm, 13mm and 20mm respectively, and the maximum displacements all occur at the lower part of the dam abutment excavation face.



(a) 10th layer



(b) 18th layer



(c) 27th layer

Figure 6. Displacement clouds of the slope of the shoulder of the dam.

Because the explosive uniform load applied in each excavation layer is the same in the calculation, the displacements under blasting excavation in the 10th, 18th and 27th layers are obviously different. It is mainly due to the excavation transient unloading under high ground stress and the different excavation volume caused by the gate shape of the dam abutment groove with the design contour of "upper narrow and lower wide". Therefore, in the actual project, when the dam abutment is excavated from top to bottom, the excavation volume of single blasting should be gradually reduced, and the blasting excavation zone should be reasonably designed to reduce the impact of blasting excavation on the stability of the dam abutment slope.

4 CONCLUSION

Based on the numerical simulation analysis of the dynamic response characteristics of the cave-type excavation at the left dam abutment of Zhongyu Hydropower Station, the following main conclusions are obtained.

(1) The blasting peak vibration velocities on the upstream and downstream sides of the dam abutment groove present local elevation amplification effect. Within the range of 20~100m from the explosion source in the vertical direction on both sides of the dam abutment groove, both the peak vibration velocity and the maximum principal stress of the particle in the vertical direction present extremely obvious elevation amplification effect.

(2) There are obvious differences in the attenuation phenomenon of blasting vibration velocity on the upstream and downstream sides of the dam abutment groove due to the different overhangs. The peak blasting vibration velocity of the downstream side with large overhang in the transverse river direction (Y direction) is obviously higher than that of the upstream side.

(3) During excavation in a certain layer, the displacement change rate of particles on the upstream and downstream sides of the dam abutment is usually fast first and then slow, and there will be obvious inflection points.

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