Dynamic disturbance damage of rock mass in layered blasting of deep underground plant

WU Liang1,2*, LI Tianci2, XIANG Xiaorui2, HU Jiayi3

1. Hunan Provincial Key Laboratory of Key Technology on Hydropower Development, Changsha, Hunan 410014, China
2. College of Science, Wuhan University of Science and Technology, Wuhan 430065, China
3. College of management, Wuhan University of Science and Technology, Wuhan 430065, China

*Corresponding author’s e-mail: wuliangwust@sina.com

Abstract: This paper established a constitutive model for rock dynamic tension based on HJC and TCK, and achieved the material model embedding through the LS-DYNA UMAT secondary development module analyzed the effect of blasting load, in-situ stress unloading and coupled load on damage distribution of surrounding rock of factory building during layered excavation. Studies have shown that the damage degree of the surrounding rock near the outline of the plant is the largest during the blasting excavation of deep underground powerhouses; when the in-situ stress level is low, the surrounding rock damage near the excavation surface is mainly affected by the blasting load, when the in-situ stress level is high, the surrounding rock damage near the excavation surface caused by the blasting load will be squeezed by the ground stress; in the remote excavated area, the surrounding rock damage is mainly caused by the redistribution of in-situ stress.

1. Introduction

Rock mass of deep buried underground plant is under high in-situ stress conditions, excavation causes rock mass stress redistribution, Maleki H [1] and Carter B J [2] have studied the excavation of deep-buried tunnels and found that after deep blasting excavation, the closer the rock is to the cave wall, the greater the stress difference between surrounding rocks at the same interval and the greater the corresponding stress gradient between rocks. Rocks blasting and excavating under a stress gradient will exhibit special mechanical behaviors, such as common rock bursts. Existing results have made it clear that blasting excavation of deep-buried rock mass is a dynamic process with high strain rate, the rock mass will be subjected to impact compression under blasting, and the rock mass will be subjected to unloading tensile stress after unloading in-situ stress. The tensile strength of the rock is much smaller than its compressive strength, so the failure under tensile load should also be considered in the rock constitutive model. Although the finite element method has been widely used in engineering, the accuracy of the simulation results depends on the accurate material constitutive model. Establishing dynamic damage constitutive model of rock materials under high stress and high strain rate is the basis for the study of deep blasting excavation unloading damage problems.

Therefore, based on the HJC and TCK material models, this paper constructs a constitutive model of rock dynamic tensile and compression damage, uses the TCK material model to describe the brittle
tensile damage of rocks, considering the evolution of damage and the relationship among average stress, crack density and volume change rate \[3\]; The HJC material model is used to describe the compressive damage of rock, considering the relationship between dynamic compressive strength and pressure, damage softening and strain rate effect \[4\]. Finally, the constitutive subroutine of rock material is written in Fortran language and embedded in the dynamic finite element software LS-DYNA, and the damage simulation analysis of the blasting and excavation process of the deep underground plant is carried out.

2. Engineering background
As we all know, the drilling and blasting method is still the main mining method during the rock masses excavation of deep buried underground plants, the mining scale of the underground plant is huge, the digging depth can reach hundreds of meters, and the maximum principal stress in the excavation area can reach 20 ~ 30MPa \[5\]. In order to ensure safe excavation, the excavation plan is generally based on top-down layered excavation. In order to introduce the excavation procedure more clearly, this article will take the rock body excavation of Pubugou underground powerhouse as the research background.

Pubugou Hydropower Station is a river-controlling dam project of stair-like hydropower in Dadu River Basin and one of the key projects of stair-like hydropower in Dadu River Basin, the underground factory of the hydropower plant has a large mining scale, with an excavation depth of 220-360 meters and an excavation size of 294.1 meters × 307.7 meters × 70.2 meters (length × width × height) \[6\]. The rock characteristics of the workshop excavation area are medium-coarse-grained granite, and the rock masses in the excavation area are mainly type II and III rock masses, the stress field in the excavation area of the underground plants is a medium and high stress field mainly based on structural stress; As shown in Figure 1, the main stress distribution characteristics of the main plant are: the angle between the first main stress direction and the longitudinal axis of the main plant is 20 ~ 30 °, and the directions of the first and third main stresses are approximately horizontal. The first main stress is 21.1MPa ~ 27.3MPa, the third principal stress is 10.2 MPa ~ 12.3MPa; the direction of the second principal stress is basically vertical, and the magnitude of the second principal stress is 15.5MPa ~ 23.3MPa, the in-situ stress level of this underground powerhouse belongs to medium-high in-situ stress conditions \[7\]. The factory buildings are often excavated by drilling and blasting in layers from top to bottom. The schematic diagram of the layered area excavation procedure is shown in figure 1. Generally, in the excavation of the same layer of rock mass, the excavation sequence of "pulling in the middle first and then expanding on both sides" is selected.

3. Numerical simulation of layered blasting excavation of underground plants

3.1. Calculation model and parameters
In order to eliminate the influence of the boundary in the dynamic calculation, the rock mass with a side length of 200m × 200m is used for calculation, and the thickness of the intercepted rock as a calculation model is 1m. Vertical far site stress of excavated factory buildings \(\sigma_y=20\) MPa, horizontal far site stress \(\sigma_x=10\)MPa. The bottom of the model is constrained in the vertical direction, and a total of 79122 solid elements are excavated in the third layer. Establish a finite element model based on the schematic diagram of the plant in Figure 1, take a single-layer unit, refine the grid, and finally establish the finite element model and boundary conditions as shown in figure 2.

According to St. Venan's principle, in the dynamic numerical calculation, the explosive impact load on the wall of the blast hole can be equivalently added to the boundary of the crushing area, According to literature\[8,9\], the theoretically analyzed explosion load time-history curve is drawn as shown in figure 3, on the basis of which, the theoretical load curve can be simplified into a triangular load, as shown in figure 4. Finite element calculation using simplified triangular blasting load only needs to determine the peak blasting load \(P_0\), explosion load rising time \(t_r\) and explosion load duration \(t_d\). Since the simplified basic load information is retained, the calculation accuracy can meet the engineering
needs.

Figure 1. Schematic diagram of the excavation procedure and principal stress of the underground powerhouse of Pubugou Hydropower Station [7] (unit: meter)

Figure 2. Finite element model and boundary conditions

The self-made rock dynamic tensile and compression damage material model is used in the calculation. The rock material parameters used in the calculation model [10]: the rock density is 2.84 g/cm³, modulus of elasticity is 18 GPa, Poisson's ratio is 0.2, compressive yield strength is 106 MPa, hardening parameters is 1.0, the initial bulk modulus of rock mass is 6.44×10²⁵ m⁻³, Weibull distribution parameter is 7.0, fracture toughness of rock is 5.8×10⁵ N·m⁻³/².

Figure 3. Explosive load and dynamic unloading curve of in-situ stress

Figure 4. Simplified curve of explosive load and dynamic unloading of in-situ stress
3.2. Distribution of surrounding rock damage during layered blasting excavation of rock mass

According to the existing results, the disturbing load on the rock mass in the blasting excavation engineering of deep buried rock mass is the coupling effect of the explosive load and the unloading load of the ground stress. Before the plant is excavated, the rock mass in the area to be excavated is clamped by the ground stress, and the initial surface stress exists. After excavation, the elastic deformation in the rock mass is released, which will cause disturbance on the excavation surface. The form of stress wave propagates to the farther excavation area. The rock stress and tensile stress included in the dynamic stress during the excavation of the powerhouse. After excavation, the ground stress of the powerhouse is distributed again and a stress gradient is formed. With the increase of the number of excavation layers, the stronger the squeezing effect on the excavation area, the greater the stress gradient of the surrounding rock of the plant under the action of in-situ stress, and the damage characteristics of the surrounding rock of the plant after excavation depend on the stress field of the surrounding rock. The degree and scope of rock damage are also different. In this paper, the excavation layer excavation of the third to seventh layers of the deep underground powerhouse is selected as the research background, and the damage distribution law of the surrounding rock of the different excavation layers under the action of in-situ stress is analyzed.

3.2.1 Surrounding rock damage caused by direct unloading of ground stress

In the process of calculating the damage of the surrounding rock of the plant under the action of unloading the ground stress. First, static stress calculation is performed by ANSYS implicit solver to obtain the original rock stress field, and the nodal stress on the equivalent boundary of the area to be excavated is extracted under the original rock static field. Excavation on the equivalent boundary. According to the equivalent blasting load loading method, the in-situ stress unloading time $t_{du} = 2ms$. The damage distribution of the surrounding rock of the factory buildings in different excavation layers at 100ms after excavation is shown in figure 5.

![Figure 5. Damage distribution of surrounding rock of factory buildings with different excavation layers under direct stress unloading](image-url)

It shows the distribution of the surrounding rock damage range after the layered excavation of the underground powerhouse stabilizes the stress in figure 5. The layered excavation adopts the middle trough, and a 4-meter protective layer is reserved. The amount of excavation is within the range of the same section of detonator initiation and crushing rock mass. From the results of excavation and unloading damage, it can be seen that during the excavation of the third to seventh layers, due to the blasting excavation of the upper rock mass, the area to be excavated is formed vertically to form a new free surface, and the side walls and arches near the outline of the plant. The top surrounding rock produced a certain amount of damage.

It can be seen from figure 5 that the damage degree of the rock mass on the contour surface of the factory building is the most serious, and the damage degree is reduced as the distance away from the contour surface; the damage degree on the vault of the factory building is small but the damage depth
is large; with the excavation layer. The increase in the number is due to the greater the clamping effect of in-situ stress on the rock mass to be excavated, the greater the dynamic effect of the rock mass after excavation, and the greater the tensile stress generated after the unloading of the in-situ stress, in the area near the excavation. The damage degree and scope of the rock mass are also larger; affected by the distance and in-situ stress, with the increase of the number of excavation layers, the damage depth of the surrounding rock of the vault in the far excavation area increases first and then decreases. The surrounding rock of the vault has the largest damage range during excavation, and the surrounding rock of the vault has no damage during the excavation of the layer VII.

3.2.2 Surrounding rock damage caused by coupled load
Under the coupling effect of blasting load and direct unloading of in-situ stress, the calculation process of the surrounding rock damage of the factory building. Considering the effects of blasting load and in-situ stress, the two act on the excavation surface. During the calculation, the load acts on the outer boundary of the area to be excavated. The equivalent peak explosion load $P_e$ is 60Mpa, and the peak explosion rise time $t_r$ takes 1ms, and explosion load duration $t_d$ takes 10ms. The in-situ stress is calculated by static force, and the in-situ stress is released at 8ms. The damage distribution of the surrounding rock of the factory buildings in different excavation layers at 100ms after excavation is shown in figure 6.

![Figure 6. Damage distribution of surrounding rock of factory buildings with different excavation layers under coupled load](image)

It shows the damage distribution of surrounding rock after layered excavation under the coupling effect of blasting load and in-situ stress in figure 6. After blasting and excavation, the blasting load and in-situ stress load act on the equivalent excavation surface. The rock mass failure in the excavation area mainly shows compression and shear and tensile failure, and the tensile failure is the main one. It can be seen from figure 6 that the damage distribution is mainly near the outline of the plant, and the damage degree and range are the most serious near the equivalent excavation surface. It can be seen from the damage distribution of the blasting excavation in the excavation layer of the III ~ V layer, when the number of excavation layers increases, the in-situ stress level of the excavation area increases; The effect has obvious inhibitory effect, so the damage degree and range of surrounding rock in the excavation area will decrease as the number of excavation layers increases. It can be seen from the damage distribution after blasting excavation of V ~ VII layer excavation layer. When the excavation layer continues to increase, as the stress level continues to increase, the rock damage degree and depth near the excavation area increase accordingly. This is because the secondary distribution of the in-situ stress field in the excavation area after excavation leads to new damage and destruction. The higher the in-situ stress level, the greater the damage and extent of compression and shear damage. In the excavation of the powerhouse arch surrounding rock in the remote area, the damage characteristics are the same as the damage law of the surrounding rock after the direct unloading of the ground stress. They all show that as the number of excavation layers increases, the surrounding rock damage depth increases first and then decreases. This shows that the surrounding rock damage in the excavation of the remote area is mainly caused by the secondary adjustment of in-situ stress.
When the number of excavation layers is small, that is, when the in-situ stress level of the excavation area is low, the rock damage near the excavation area is mainly affected by the explosion impact load, and the rock body is mainly damaged by tension. Increase, surrounding rock damage in the excavation area will be affected by in-situ stress. The redistribution of in-situ stress in the remote excavation area is the main cause of surrounding rock damage.

4. Conclusion
In this paper, based on the HJC and TCK material models, a dynamic compressive damage constitutive model of rock is established, and the numerical simulation of the new material model is realized through the LS-DYNA UMAT secondary development interface. Based on the newly-built constitutive model, the finite element simulation of the surrounding rock damage distribution after layered excavation of the deep-buried powerhouse has initially obtained the following understanding:

(1) Regardless of whether there is only in-situ stress or coupling effect, the surrounding rock damage near the outline of the factory building is large after the excavation, and the surrounding rock damage is the most serious in the vicinity of the excavation.

(2) Without considering the cumulative damage effect, only considering the dynamic stress unloading, the damage of the newly formed contour surrounding rock is mainly caused by the dynamic stress unloading, and the damage of the surrounding rock formed by the previous layered excavation is the current layer. After excavation, due to the further redistribution of in-situ stress, and the depth of surrounding rock damage of the contour surface formed in the previous excavation will be affected by the distance from the current excavation area.

(3) As the excavation area is constrained by in-situ stress compression, as the number of excavation layers increases, the in-situ stress level of the to-be-excavated layer increases, and the surrounding rock damage near the excavation area decreases first, with the in-situ stress level Continue to increase, due to the compression and shear failure of the rock mass when the ground stress level is high, the surrounding rock damage near the excavation will show a post-increasing phenomenon.

Acknowledgments
This work was supported by Hunan Provincial Key Laboratory of Key Technology on Hydropower Development Open Research Fund Project (PKLHD201801). The research work has received funding from the National Natural Science Foundation of China (Grant Nos. 51779193 & 51979205).

References
[1] Maleki H, Dolinar D R, Dubbert J. Rock Mechanics Study Of Lateral Destressing For The Advance-And-Relieve Mining Method[J]. 2003.
[2] Carter B J. Size and stress gradient effects on fracture around cavities[J]. Rock Mechanics Rock Engineering, 1992, 25(3): 167-186.
[3] Riedel W, Thoma K, Hiermaier S, et al. Penetration of reinforced concrete by BETA-B-500 numerical analysis using a new macroscopic concrete model for hydrocodes[C]. Berlin-Strausberg Germany,1999.
[4] Taylor L M, Chen E-P, Kuszmaul J S. Microcrack-induced damage accumulation in brittle rock under dynamic loading[J]. Computer Methods in Applied Mechanics and Engineering, 1986, 55(3): 301-320.
[5] Zhang Jian. Research on dynamic deformation failure and stability mechanism of surrounding rock in deep roadway [D]. China University of Mining and Technology, 2015.
[6] Yan Jun, Xiao Peiwei, Sun Jilin. Summary of excavation construction of underground powerhouse of Pubugou Hydropower Station [J]. Hydroelectric Power, 2010, 36 (6): 56-59.
[7] Su Pengyun. Optimal design of Pubugou underground powerhouse and numerical simulation analysis of surrounding rock stability of cavern groups [D]. Wuhan University, 2004.
[8] Wenbo L U, Yang J, Peng Y, et al. Dynamic response of rock mass induced by the transient release of in-situ stress[J]. International Journal of Rock Mechanics Mining Sciences, 2012,
53(9): 129-141.

[9] Lu W, Yang J, Ming C, et al. An equivalent method for blasting vibration simulation[J]. Simulation Modelling Practice Theory, 2011, 19(9): 2050-2062.

[10] Wang Zhi liang, Zheng Ming Xin. Numerical simulation of effect of rock blasting based on TCK damage constitutive model[J]. Rock and Soil Mechanics, 2008, 29(1): 230-234.