Summary of Study on Toppling Deformation of Rock Slope

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Abstract: The toppling of anti-dip layered rock slope is a typical mode of rock slope failure. Because this kind of deformation phenomenon is very common in hydraulic engineering and highway engineering, it has been paid more and more attention by the engineering community. The deformation mode, factors affecting toppling rock slope and dumping deformation mechanism were described in this paper.

1. Introduction
Deformation and failure of rock slope is an important form of slope instability. Compared with soil slope, rock slope has the characteristics of large scale, high strength of material itself, various structural changes and complex failure modes. Moreover, the instability of rock slopes often affects the safety of large-scale water conservancy and hydropower facilities in the country. Especially in the construction of the Three Gorges reservoir area and large domestic reservoirs, the stability of rock slopes has become a key issue to be solved urgently. Studying the induced factors of rock slope, the failure mechanism of slope, and then accurately evaluating its stability and controlling measures can effectively reduce the economic loss and damage caused by slope instability, which is important in the engineering field and is about the economic development of the country and the rational use of resources. Therefore, it is of great significance to study the failure mechanism of rock slopes.

2. Deformation mode of toppling rock slope
Dump deformation and failure is a typical model of rock slope instability. It often occurs on slopes with large slopes and empty surfaces, and the rock mass is cut into columnar rock slopes by transverse joints. The dumping deformation damage is relatively slow due to the relatively slow deformation process, and the amount of deformation is small. Compared with a wide range of rock landslides and collapses, the attention is not very high. However, the dumping damage of rock mass on the slope of the road is very common. The collapse of rock mass caused by dumping damage will cause great danger to the safety of road traffic and pedestrians.
Dumping damage often occurs in anti-dip slopes of rock masses with multiple sets of joints, and is also an exception for some hard soils. The dumping deformation often occurs at the leading edge of the slope. Due to river erosion, unloading of the slope and the weight of the rock mass, the rock mass at the leading edge of the slope will bend the cantilever beam along the vertical joint to the slope. Gradually develop to the trailing edge of the slope. Due to the increase of the horizontal displacement of the leading edge of the slope, the columnar rock will produce tensile cracks at the trailing edge, and the contact relationship of the transverse joint will change. The contact of the previous edge will become the corner contact, forming a regular step. In the more severely bent parts, slippage occurs along the transverse joints due to excessive lateral thrust. In the medium-thick layer of hard rock, the failure form is often the collapse of the root after fracture, while in the thin layer and the lithological soft rock, the deformation is relatively slow, showing a creepy form. Under the influence of rainfall and earthquakes, the development of dumping damage will be aggravated. Dumping deformation often occurs in the shallow surface of the slope. Collapse and small-scale landslides are the main deformation modes, and there are few large-scale landslide disasters caused by deep dumping of rock mass (Martin. Dennis C. 1990) \[1\]. However, in recent years, some studies on the anti-dip layered slopes in the southwestern mountainous areas show that the depth of the dumping deformation has reached 200~300m. For example, the depth of the dumping deformation occurred in the Jinping-Santan section of the middle reaches of the Yalong River in Sichuan Province and the dam site of the Miaowei Hydropower Station in the Minjiang River reached hundreds of meters, and a large number of cracked subsidence areas were formed at the top of the slope due to the depth dumping. (Huang, 2007) \[2\].

3. Research status of toppling rock slope

3.1. Influences affecting toppling rock slope

There are many factors affecting the dumping deformation of rock slopes, such as slope shape, rock strength, structural plane strength, joint development type, rainfall, earthquake, groundwater and other factors will have an impact on the dumping deformation process. Han Beichuan and Wang Sijing (1999) \[3\] summarized the influencing factors of dumping damage: initial horizontal stress, slope shape and angle, rock mass strength and structural plane shear strength, structural surface occurrence and spacing, water level Change, etc. Further research shows that the above factors only affect the dumping deformation within a certain range. Even if it is studied in terms of pure theory, it will be found that most of the above factors affect the stability of the slope as a whole, rather than the deformation of the slope. Influences. Xu Peihua et al. (2004) \[4\] concluded that the deep dumping deformation of the left bank slope of Jiefanggou does not have the deformation characteristics of the conventional mid-upper crack and bottom slip. The reason for the deformation is the release of the slope foot stress due to the rapid undercut of the river. And the combination of deep rock mass bending. Moreover, during the process of river valley cutting, the deformation evolution of high and steep slope is divided into three stages: stress release of slope foot, stress reorganization of rock mass, surface transformation process to drive rock mass failure, and deformation after slope stability. The aging deformation process and the destruction stage of the potential failure zone. Huang Runqiu (2004) \[5\] and other research results show that the mechanical mechanism of the dumping deformation of rock slope is that the stress at the root of the layered rock mass is greater than the tensile strength of the rock column itself, so that it breaks at the root of the rock mass under the action of self-weight.

In the study of the influencing factors of dumping deformation, rock mass strength, joint spacing, rock dip angle and structural plane strength are generally the main influencing factors, while the study on the effects of water pressure, weathering and slope unloading on dumping deformation is relatively less. Li Tianfu (2006) \[6\] believed that Goodman & Bray's model did not consider the effect of water pressure, and could not explain some unconventional dumping deformation phenomena. For example, some steep slopes of bedding slopes will also undergo dumping deformation damage. Considering the influence of water fissure water pressure, this dumping phenomenon can be better explained. He also
summarized the process of dumping deformation under water pressure as follows: rainfall, surface water produces dumping moment in rock mass fissure, water head difference is generated between the front slope and the rear slope, and the slope is successively generated from the leading edge to the rear. Dumping, when the range of dumping continues to expand, there will be a continuous dumping phenomenon. Chang Zufeng et al. (1999) considered that the initial stress field of rock mass is the cause of dumping in the Xiaolangdi project reservoir area. After the reservoir is impounded, the weaker water layer in the rock mass will reduce the occurrence of dumping deformation or sliding along the weak surface.

In summary, the dumping deformation of rock mass slope is a slope failure mode controlled by many factors. In the actual engineering analysis, various factors need to be considered to study the process of dumping deformation and its deformation mechanism. Among these factors, joint production, layer thickness, structural plane and rock mass strength are the main controlling factors, which require great attention, and other factors such as groundwater, rainfall, earthquake, etc. need to be analyzed in combination with actual working conditions.

3.2. The research status of dumping deformation mechanism

The problem of toppling rock slope was valued by the engineering community in the 1970s, and many experts discussed it as a typical rock slope instability mode. In 1973, Frietas & Watters studied the dumping deformation of rock mass as a typical failure mode and caused damage in various rock masses. Brabb & Harrod summarized the landslide hazards worldwide and made a detailed classification, and pointed out that dumping deformation is a widespread phenomenon when slopes are destroyed. When analyzing the slope deformation, it can not be studied according to the conventional method of finding the sliding bed, sliding surface and sliding body. It is necessary to fully consider the influencing factors such as joint spacing and structural surface strength, and the development process of its dumping deformation. research. At present, there are three main research methods for dumping deformation: limit equilibrium method, physical model test method and numerical simulation method. The specific research progress is as follows.

1) Limit equilibrium method

When analyzing the slope stability, if the assumption of the limit equilibrium condition is satisfied and only the final failure mode is concerned, the limit equilibrium method can be used as a preliminary estimate for the slope analysis, considering the rock mass in the overlying load and water. The limit equilibrium rule under pressure is more practical (Zou Lifang, 2009). Goodman & Bray (1976) first proposed the limit equilibrium-based analysis method (referred to as GB method), which is one of the most effective and important means in the calculation of rock slope dumping deformation. The method divides the dumped slope into several The bars are then statically balanced to calculate their stability. Duncan (1992) improved the G-B model, and considered the effect of water pressure between layers and the effect of overlying load on the dumping deformation, and gave a mathematical expression formula. Wang Xiaogang et al (1996) proposed to use the generalized geomechanical model to study the dumping deformation and failure of rock mass slopes, and corrected the limit equilibrium analysis theory of Goodman & Bray, which considered the role of rock bridge and improved the failure mode. The method of determination is also used to study the dumping failure of rock slopes. Li Tianfu et al. (2006) considered the influence of external load factors and water pressure on dumping damage on the basis of Goodman & Bray limit equilibrium method, and gave the basic analytical formula. Zhu Jiliang et al. (2004) proposed a calculation method based on block theory under the consideration of factors such as water level rise and fall, seepage flow and seismic load.

The limit equilibrium method is also limited by the factors such as layer thickness, rock mass strength and slope shape in the study of dumping deformation. For soft rock with small rock mass strength and thin rock mass with thin layer thickness, this method will not Apply again. This method considers the simple failure mode of uniform medium, and the dumping deformation damage of rock mass is greatly affected by factors such as joint spacing and structural plane strength. In this method,
these determinants are not considered, so its Applications in actual engineering have received restrictions. D.P. Adhikary (2007) \cite{15} suggests that the calculation results of the limit equilibrium method will deviate from reality when the joint friction angle is small. Some scholars believe that when the dumping deformation occurs, the deformation motion form and deformation mechanism of the slope top, the slope and the slope foot are completely different. The limit balance method assumes that the sliding surface method is no longer applicable here.

(2) Physical model test method

The physical model method can intuitively simulate the magnitude and distribution of rock mass stress in the slope, and can accurately measure and record the deformation and development process of rock mass slope, but it also has shortcomings such as long cycle and high cost. Less. Zuo Baocheng (2004) \cite{16,17}, Lu Zengmu (2006) \cite{18} and others obtained the anti-dip layered slope mainly by dumping and fracture, and also found that the rock mass thickness and structural surface strength are the important factors affecting the dumping of rock slopes are small, and the influence of rock dip on the dumping deformation is small. The anti-overturning ability of rock mass increases with the increase of structural plane strength and rock thickness. Huang Runqiu et al. (1994) \cite{5} obtained the relationship between dumping depth and slope gradient, occurrence by model test. This research has great practical significance. If we can study the development process and deformation depth of the dumping deformation by studying the inclination angle and the slope foot, this greatly simplifies the research process compared with the analytical mechanism to study its deformation mechanism. Luo Huayang et al. (2000) \cite{19} carried out a model test on the slope of Wuqiangxi Hydropower Station, simulated the effects of rock mass fissure water pressure, self-heavy stress, excavation unloading and other factors, and obtained the role of fissure water pressure and rock. The results of the deformation and magnitude of the body deformation were significant, and the deformation was obvious after the slope excavation unloading. The results were compared with the results of the geological analysis and found to be more consistent. Zuo Baocheng (2005) \cite{16} proposed that the failure process of the anti-dip layered slope has obvious characteristics of “superimposed cantilever beam”. D.P. Adhikary (2007) \cite{15} found through centrifugal test that when the friction angle of the rock mass is large, the form of dumping deformation is transient, and when the friction angle of the surface is small, the form of dumping deformation is progressive. The range of the friction angle determining the failure mode is 20 to 25 degrees.

In summary, the model test can obtain some deformation laws of slope dumping damage, but since most models are simple, and some factors that have important influence on dumping are difficult to achieve through model tests, the physical model is complex with the actual rock mass. The state is difficult to agree, so the results have certain limitations. Therefore, the model test should strengthen the study of the influence of groundwater, rock mass thickness, structural plane shear strength, initial stress and other factors on the dumping deformation, which also puts higher requirements on the model design.

(3) Numerical simulation method

The numerical simulation method is a method for studying the stability of slopes, which is gradually developed in this year, because its low cost, the calculation results are relatively intuitive, and it can simulate complex conditions that cannot be performed by various physical test methods. The engineering community has been widely used. In the study of the dumping deformation of rock slope, the step-by-step dumping deformation process of the slope is the focus of research. The numerical simulation method can clearly and intuitively reflect the whole process of the slope being gradually dumped, and the unit block in the model can be obtained. The key parameters such as displacement field and stress field during the deformation process are of great significance for studying the mechanism of dumping deformation. Therefore, this method has its unique advantages in the study of dumping rock slopes. The current numerical simulation methods mainly include continuum mechanics method and discontinuous medium mechanics method, and the main research is as follows.

a. Continuum mechanics method
Common continuum mechanics methods are finite element method and finite difference method. Han Beichuan and Wang Sijing (1999) [3] After considering the viscous characteristics of rock mass, the overall deformation of the dumping rock mass is divided into elastic deformation and viscoplastic deformation, and the constitutive relation of viscoplasticity is proposed. This relationship can also be used as a constitutive relationship of the structural plane. Xu Peihua et al. (2004) [20] used FLAC3D software to simulate the deformation mechanism of the dumping slope when the valley is rapidly undercut. It is concluded that with the undercut of the valley, the principal stress direction of the rock mass will be obviously deflected, and the rock mass Unloading rebound is the cause of deep rock mass dumping. Chang Zufeng (1999) [7] applied nonlinear theory to numerical simulation of the dumping slope in Xiaolangdi Project, and considered the influence of filler between structural planes, and processed the high angle joint into contact unit, which was obtained. Time monitoring is more consistent. J.S. OBERG (1999) [21] used FLAC software to carry out a large number of numerical simulations on the dumping phenomenon of rock slope, and summarized its dumping mechanism. Li Guirong (1997) [22] used the finite element method to numerically simulate the stage excavation of the slope. The material selection was elastic viscoplastic material, and various yield criteria were selected. The displacement of the simulation results was close to the measured displacement. The reason for the error in the displacement value is that the model uses elastic viscoplasticity and there is elastoplasticity in the actual rock mass.

The finite element method based on the Cosserat theory can better simulate the bending effect of the dumping rock mass and is a good continuum mechanics method. Yan Chengxue (1994) [23-24] used Cosserat theory to calculate the bending phenomenon of layered rock mass, and the results are consistent with the results of equivalent continuous medium. The theory is also applied to the rock mass slope of Longtan Engineering. The feasibility of the method is verified by the calculation of the ground stress. D.P. Adhikary [25] also used the Cosserat theory to calculate the finite element of the rock slope, and the results obtained are also more credible. In general, this method is a good method to study the dumping deformation of rock mass, but because the yield criterion of classical continuum mechanics is not applicable here, it is necessary to develop its corresponding yield criterion.

b. Discontinuum mechanics method

However, in the actual rock slope dumping problem, it can be found that the rock mass is cut by the anti-dip structure surface into discrete but mutually powerful blocks. When the dumping damage occurs, the block unit will translate and rotate. A variety of deformation modes, such as the discontinuous medium mechanics method, can better calculate the deformation mode.

J.S. OBERG (1999) [21] used UDEC software to study the mechanism of slope dumping deformation, and summarized the whole process of development of dumping deformation. F. Lannro et al. (1997) [26] used the discrete element method to simulate the dumping deformation of the block, and considered the influence of the structural strength of the rock mass and the velocity distribution on the contact surface on the dumping deformation. Sun Yadong et al. (2002) [27] used the discontinuous deformation method (DDA) to numerically simulate the slope dumping under different strength parameters, and obtained the deformation mode of the block as the dump-slip composite. For plane-to-plane contact rather than point-to-plane contact. Liu Hongyan et al. (2006) [28] used numerical manifold method to simulate the dumping deformation failure of layered rock mass slopes, and discussed the mechanism of dumping deformation. Cheng Dongxing (2005) [29], Hu Yadong et al (2014) [30] used 3DEC software to analyze the dumping deformation factors and deformation mechanism of rock slopes.

Among many non-continuous media mechanics methods, the discontinuous deformation method (DDA) can simulate the large deformation of the block, and can simulate the rotation characteristics of the element, which has its unique advantages in analyzing the dumping deformation of the slope.

4. Conclusion

There are many factors affecting the slope deformation of rock slopes, such as ground stress field, rainfall infiltration, rock dip angle, structural plane strength and other factors. At the same time, since
the dumping deformation is a dynamic process, the deformation process is complicated. Combined with other influencing factors, a comprehensive study can be conducted to consider the slope dumping deformation process under different influencing factors.

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