A Summary of Study on Slope Stability under the Coupling of Vibration and Rainfall

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Abstract. Systematically discussed the significance of the study on the influence of the coupling of vibration and rainfall on the stability of slope. The mechanism of slope hazards under the coupling action of vibration and rainfall was pointed out. The research status of the effects of vibration and rainfall coupling on slope stability is reviewed from three aspects: basic theory, analytical calculation method and application in slope engineering. Based on the analysis of the status quo of these studies, this paper proposes the problems and shortcomings in the study of the influence of the coupling of vibration and rainfall on the stability of slope.

1. Introduction
There are many mountains in China with a large number of natural high-steep slopes, and a large number of high-steep slopes will be formed during the construction of the foundation project. In engineering examples, multiple factors such as vibration and rainfall are often combined to work together. At present, the study on the stability of slope by the coupling of vibration and rainfall is mainly to comprehensively consider the influence of the change of seepage field caused by rainfall on the stability of slope [1], the inertial force of vibration increases the slippage factor of the slope and the continuous action of vibration. Shear stress in the surrounding rock is increased caused by the continuous action of vibration, which affects the overall stability of the slope [2]. This paper summarizes the main research status from three aspects: basic theory, analytical calculation method and application in slope engineering. And in view of the problems existing in the current research, I put forward my own views on the future development direction.

2. Basic theory

2.1. Seepage theory
The research on the influence of seepage on slope stability has been nearly 200 years old. In the 1950s, French engineer Henri. Darcy [3] obtained the relationship between seepage velocity and head loss through a large number of seepage experiments. This is Darcy's law. Seepage refers to the activity of a fluid in a porous medium, and the stability of the slope is affected by active water from multiple angles. Many engineering practices have shown that water plays a role in most slope damage. The slope will withstand the hydrodynamic pressure generated by the seepage of water, and the saturated fissure will be subjected to the hydrostatic pressure of the fracture water [4]. In addition to the above effects, water also has the chemical and physical effects of etching and softening the slope, and the water scouring effect will also damage slope.
2.2. Vibration theory
The causes of vibration can be roughly classified into two types: blasting vibration and earthquake vibration. Both conditions will have a great impact on the stability of the slope. The influence of vibration on the stability of slope is mainly reflected in two aspects: the inertia instability caused by the vibration inertial force; the attenuation instability caused by the continuous increase of shear stress in the slope due to cyclic degradation [5]. During the blasting construction process, the rock and soil near the blasting area directly under the impact of the blasting wave, and the stress wave propagates along the rock and soil. As the distance increases, the strength of the stress wave gradually decreases. For the geotechnical body at the far distance, it can not directly cause damage, but for the weak structural surface (fracture), the stress wave is reflected and projected on the structural surface (fracture surface), and the structural surface (fracture surface) will expand and extend. For engineering, because of multiple frequent blasting, the original structural plane, structural plane, and cracks gradually extend until they penetrate, eventually losing stability. This process is called “cumulative damage effect” [6].

2.3. Coupling theory of vibration and rainfall
The focal point of the coupling between vibration and rainfall is the time-space relationship between vibration and rainfall. The first consideration is the condition that the earthquake cause slope stability changed after the change of the seepage field of rainfall, first is the rainfall seepage calculation, and then is the vibration for dynamic calculation [7]. Secondly, considering the condition that the earthquake first happen than rainfall caused slope sliding, the model at the critical value of landslide is selected for rainfall analysis [8]; finally, the condition that considered simultaneous action of rainfall and vibration, the change of seepage field caused by rainfall Consider the role of shock waves at the same time.

The attenuation of stress waves caused by vibration is a very complicated process. Therefore, when the current research simulates the impact of blasting on slopes, most of them only consider the influence of single blasting on the slope. The effect of the attenuation of the wave on the slope can be considered in the next step. In addition, the working conditions of the simultaneous action of rainfall and vibration are difficult to calculate. Therefore, the research on related aspects needs to be improved.

3. Theoretical calculation
The method of theoretical research mainly uses the limit equilibrium method under pseudo-static force, and the related content of hydraulics and fracture mechanics is used to analyze the stability of slope soil under the condition of coupled vibration and rainfall conditions.

3.1. Theoretical calculation under blasting vibration and rainfall coupling conditions
Wang Jianming and Chen Zhonghui used the theory of fracture mechanics to analyze the variation of the stress intensity factor at the crack tip of the slope during blasting excavation and hydrostatic pressure [9]. According to the stress intensity superposition principle, the stress intensity factor formula of the crack tip edge under the combined action of rainfall and blasting is derived, which is used as the crack initiation criterion under the double working conditions of blasting and rainfall. Based on the Griffith energy criterion, the sliding instability process of the slope sliding body is explained from the energy point of view, and the sliding distance along the bottom sliding surface after the sliding block broken is deduced.

3.2. Theoretical calculation under coupled seismic and rainfall conditions
Wu Yong, He Siming, and Luo Wei based on the hydraulic formula, using the upper bound theory of limit analysis, obtained the criterion of rock slope stability, that is the internal energy loss rate is greater than the external force power; from the perspective of rock fracture mechanics, analysed the crack propagation, slope infiltration and slip surface formation mechanism of the slope; it is pointed out that the crack of the damaged slope after the earthquake has a critical depth that can extend
by the crack water and may penetrate the weak interlayer, and the limit length on the weak interlayer seepage area that can decided the stability of slope [10].

The limit equilibrium method has early application and rich experience. Although the limit equilibrium method used in the stability analysis of slope is much, the limit equilibrium analysis applied to the coupling of vibration and rainfall is rare; For the stability analysis under the action of vibration and rainfall, since the calculation of hydrodynamic pressure in the current formula is independent of vibration, the existing algorithm is equivalent to simply superimposing the effects of vibration force and groundwater. How to create more theoretical calculation formulas for slope stability analysis under the coupling of vibration and rainfall, and better coupling the two working conditions remains to be studied.

4. Numerical analysis

Due to the complicated working conditions of the coupling of vibration and rainfall, the theoretical calculation method is often used to superimpose the two working conditions. The numerical analysis method has the advantage that can analyze the discontinuous and heterogeneous slope of any shape and does not need the preset sliding surface, and the numerical analysis method can couple the vibration and the rain condition. So numerical analysis is the most widely used. The numerical analysis method of slope is mostly combined with concrete engineering examples. According to their different genesis the slopes in engineering cases are divided into natural slopes, artificial slopes, etc. So the classification of natural slopes and artificial slopes is discussed below.

The existing numerical simulation analysis methods for slope stability include finite element method (ANSYS/ABQUSE), finite difference method (FLAC3D), and discrete element method (UDEC/3DEC/PFC). The following is a description of the research and application of various methods.

4.1. Finite element method

4.1.1. Natural slope finite element method
Lin Yuchen used ABAQUS software to establish a three-dimensional model, which analyzed the stability and deformation law of the slope under the earthquake conditions, heavy rain, long-term heavy rain and several days of heavy rain, the most unfavorable rainfall and seismic coupling conditions [11]. Through the stability analysis of the slope after the anchor is arranged at different positions of the slope (slope top, slope middle, slope foot) under different working conditions. It is concluded that the overall stability of the slope is significantly improved under the coupling of rainfall and seismic loads, and it is better to arrange the anchors at the middle of the slope than to arrange the anchors at the top of the slope and the foot of the slope. SammoriꞏT simulated the transient seepage process through the Galerkin finite element method, and studied the changes of the mechanical parameters for the slope under earthquake and rainfall conditions [12].

4.1.2. Artificial slope finite element method
Yu Shuyang used finite element ABAQUS software and finite element strength reduction method to carry out finite element analysis of slope [13]. Based on the simulation analysis of the artificial excavation slope, the influence of excavation on the stability of the slope is added based on the analysis of the coupling effect of vibration and rainfall. It is concluded that the slope of the excavation will change the boundary of the slope, and the stress field of the slope will be redistributed, resulting in stress concentration, which will make the local vertical stress larger.

The finite element method is an ideal method. The basis is the variational principle and the weighted residual method. It can determine the potential sliding surface of the slope under different working conditions, and can also obtain the relevant data such as stress and strain. The selection of the model will have a greater impact on the calculation results of the finite element method, and the input of the parameters will make the results different. These are the limitations of the application of the finite element method.
4.2. **Finite difference method**

4.2.1. **Artificial slope finite difference method**
Wang Zhanqi, Yuan Haiping used FLAC3D numerical software and monitoring data of dangerous location monitoring points to calculate and analyze the stability of loose rock pile slope under natural, heavy rain and earthquake state [14]. In addition to the conventional analysis, this study also carried out the simulation study of anchor anti-slide pile reinforcement. It is concluded that the anchor shaft force in the heavy rain state and the earthquake state increases sharply after the anchor anti-slide pile reinforcement, which plays a good role in the slope.

4.2.2. **Natural slope finite difference method**
Based on the FLAC3D fish platform, Chen Wuyi compiled a slope rainfall program to study the effects of rainfall intensity and rainfall duration on slope stability [15]. In this study, the change of pore water pressure in slope is used as an index to measure the influence of matrix suction change on slope stability under different working conditions. The damage mechanism of rainfall and seismic coupling on slope is studied from the perspective of matrix suction change.

In the case of large deformation, the traditional solution based on linear assumptions to simplify the consolidation control equation is not reasonable. The finite difference method can solve the excessive Deformation of slope and has a good guiding effect on practical engineering.

4.3. **Discrete element method**

4.3.1. **Natural slope discrete element method**
Based on the theory of granular media, Ding Jianhui considers the effect of seepage on the slope, The large deformation and fluid-solid coupling of the medium. The particle flow (PFC2D) software is used to establish a numerical calculation model considering the rainfall, earthquake and coupling of rainfall and earthquake conditions. Analyzed and simulated the landslide slip, Compared numerical analysis results [8].

4.3.2. **Artificial slope discrete element method**
The slope instability is divided into three stages: start-up, acceleration, and stagnation. The stress wave of blasting is simulated by LS-DYNA, and the influence of blasting and rainfall on the slope is analyzed by UDEC [16].

Because the deformation and failure of the slope under different working conditions have nonlinear characteristics, the discrete element method is one of the most effective methods to study the stability of the slope under the coupled conditions of vibration and rainfall.

5. **Conclusion**

Comprehensive analysis of the finite element analysis methods used above leads to the following conclusions:

1. Since the cyclic blasting effect is a very complicated process, when calculating and simulating blasting have an impact on the slope, only the impact of a single blast on the slope is considered. In the next step, the rainfall and the cyclic blasting may be considered. Analyzing the influence of slope can also be introduced into the fluid-solid coupling to calculate the interaction between vibration and water.

2. The rainfall infiltration will cause the pore water movement parameters and soil shear strength parameters of the soil in the slope to change continuously. There are few studies for the anisotropic seepage influence on slope. Therefore, the study of the seepage influence on the change of soil
mechanical properties in the slope needs further research. The coupling analysis of soil, water, gas and other factors under rainfall infiltration is still to be further studied.

3. The damage of slopes under seismic loading tends to be diverse. In the past, weak layers, cracks and joints in the slope were often not considered in dynamics calculated. Fracture propagation under earthquake will provide infiltration passage for pore water infiltration, and the existence of weak interlayer may lead to liquefaction phenomenon to accelerate slope instability under the coupling effect of rainfall and earthquake.

4. The existing theoretical calculation formula for slope stability analysis under the coupling of vibration and rainfall simply superimposes the effects of seismic force and groundwater, and in reality is the coupling of two working conditions, so how to create more theoretical calculation formula for the slope stability analysis under the coupling of vibration and rainfall, and coupling the two conditions remains to be studied.

5. The research on the coupling of earthquake and rainfall is mostly concentrated in the rock slope. The stability analysis of the soil slope under earthquake and rainfall conditions needs to be developed. There is no relevant research on the stability analysis of foundation pit under blasting and rainfall conditions.

6. It is well known that in the field of basic mechanics research, experiment is an important research method, but the research on the coupling of vibration and rainfall focuses on theoretical calculation and numerical analysis, experimental methods often used only in vibration condition or rainfall condition. How to use the experimental method to simulate the landslide process of the slope under the coupling of vibration and rainfall is a direction that needs to be developed.

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