Research Progress on Dynamic Stability of Layered Rock Slope

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Abstract. The analysis of failure mechanism and stability of rock slope under seismic load has become an important research content in geotechnical engineering, and the layered structure is the most common among the rock masses composing the slope. In this paper, the layered rock slope is divided into three types, i.e., horizontal, bedding and anti-dipping, according to the dip angle of rock layer in the layered slope. The influence factors, failure modes and dynamic stability of the three kinds of slope under seismic action are systematically summarized and reviewed in detail, and the problems to be studied and the possible research approaches are pointed out in the light of the current research methods.

1. Introduction
The instability of rock slope under seismic action is one of the most important problems in geotechnical engineering and engineering geology. With the construction of many large-scale projects such as water conservancy, hydropower, open-pit mining and transportation engineering, the problem of dynamic stability of rock slope has been gradually discovered and exposed, which has become the key and difficult problem of restricting this kind of engineering construction, and has gradually attracted the attention of scholars and engineers at home and abroad. At present, the commonly used slope stability analysis methods are pseudo-static method[1], pseudo-dynamic method[2], Newmark sliding block analysis method[3], time history analysis method[4], numerical simulation analysis method[5], physical model test method[6], etc. Layered structure as one of the most common structures of rock slope, the study of its dynamic stability is particularly important.

A lot of engineering practice shows that the stability and failure mode of layered rock slope with different dip angle are different under seismic action, so it is of great practical significance to analyze the dynamic stability of layered rock slope. In this paper, according to the dip angle of rock strata, the layered slope is divided into three types: horizontal, bedding and anti-dip layered rock slope, and the research progress of the stability influencing factors and failure modes of the three kinds of slope under the action of seismic load is systematically summarized, and the existing problems and the further research direction are discussed.

2. Influencing Factors of Dynamic Stability of Layered Rock Slope
The stability of layered rock slope under seismic load can be described from three aspects: the geological environment of rock mass, the characteristics of seismic load and the structural characteristics of rock
mass itself. Among them, the geological environment of rock mass is the indirect factor, the structural characteristic is the internal factor, and the seismic action is the direct inducement factor.

2.1 Geological Environment
Layered rock slope is located in a certain geological environment, mainly including formation lithology and topographic geological conditions, in-situ stress, water, temperature and other environmental factors. As a result, the stability of the slope is inevitably influenced by external factors. The interaction between rock and water is studied by Joel A. Hurowitz et al. The stability of layered rock slope or rock slope under seismic action is analyzed by XIA Liang, KE Jian, etc. It is proved that the change of water level will cause the change of slope stability, which is unfavorable to slope stability. ZHENG Da et al. found that lithology condition is the key factor of deep dumping deformation of anti-dip layered rock slope; D.P.Adhikary et al. used two kinds of materials to carry out two sets of experiments to study the mechanism of bending and dumping failure of jointed rock slope; ZHOU Yongxiang et al. carried out research on the propagation characteristics of ground motion of different lithology, topography and geology for different rock slope, and preliminarily determined the differences in amplification coefficient, amplification effects, and spatial inconsistency under different terrain and geological conditions. H.X. Lan studied the influence of external erosion factors such as wind and sunlight on granite bodies in southern China. The influence of temperature field on the stability of rock slope can not be neglected. The damage mechanism of fractured rock mass under the action of force-temperature field and the stability analysis of slope aging are studied by CHANG Zhiguo et al. Qiu Peng et al. studied the temperature difference effect mechanism of high rock slope in high altitude area, Qu Peng et al. studied the influence mechanism of temperature field on the stability of rock slope. The influence of temperature field on rock mass is also analyzed by Tan et al. The results show that the difference and change of temperature field will change the internal stress field of rock slope, and the micro-crack and crack expansion will lead to the decrease of rock mass strength. QIAO Guowen et al. analyzed the characteristics of temperature field, stress field and deformation field of the slope under the condition of freeze-thaw by using numerical simulation to reproduce the ice splitting effect, temperature field, gravity field and water-ice phase change coupling of rock fissures under the condition of cyclic freeze-thaw.

2.2 Characteristics of Ground Motion Load
The ground motion load is a random and irregular dynamic load pulse wave, which is characterized by great uncertainty (amplitude, spectrum, duration and direction of action, etc.). The effects of different ground motion loads on the stability of layered rock slope are also different. ZHANG Miaozhi et al. studied the influence of the peak acceleration and holding time of seismic wave on the strain response of anchor bolt in anchorage slope; The influence of the peak acceleration and frequency of ground motion on slope stability was studied by NIU Jiayong, etc. FENG Xixia et al. took into account the influence of different dynamic parameters such as wave type, amplitude and frequency on the dynamic response of anti-dip rock slope. LIU Handong, JIANG Xueliang, et al. put forward that the acceleration response of layered rock slope under ground motion load is influenced by seismic wave type, frequency, duration, intensity of excitation, direction of excitation and so on. HOU Hongjuan et al. reached similar conclusions when studying the dynamic response of the horizontal structural plane. Up to now, there have been few reports on the study of the characteristics of the ground motion load considering the influence weights of various parameters of the ground motion comprehensively, which makes the selection of the characteristics of the ground motion not consistent in the analysis of the seismic dynamic stability of the rock slope.

2.3. Structure Characteristics of Rock Mass
The structural characteristics of rock mass (slope height, slope angle, bedding angle, bed spacing (rock thickness), etc.) determine the deformation mechanism, failure mode and mechanical properties of rock mass, and then affect the stability of layered rock slope under seismic action. HOU Hongjuan found
that the acceleration dynamic response of the horizontal layered rock slope is stronger than that of the homogeneous slope without structure surface. SONG Guifeng et al.[26] proposed that the changing law of structural plane parameters needs attention when studying bedding rock slopes with tension cracks. JIANG Xueliang et al.[27] found that weak interlayer has great influence on the acceleration response of horizontal layered rock slope. LIU Handong et al. [28] found that the formation, development and penetration of fractures are the main causes of the instability of anti-dip layered rock slopes. According to LI Meng et al. [29] ‘s analysis, it is found that the sliding of the mid-dip outer layered rock slope is mainly controlled by the outer structural plane of the bedding plane and the slope body, and the two joints are combined to form the sliding surface. Q. Y. BIAN Kang, HU Xunjian, et al.[30] found that the properties of discontinuous joint and rock bridge and the potential sliding surface composed of alternating combination control the degree of rock mass fragmentation, and then control the dynamic stability of bedding and horizontal rock slope. CEN Duofeng et al. [31] found that the failure mode of the block-cracked anti-dipping huge-thick layered rock slope gradually changed with the increase of the rock layer dip. Slope stability increases with the increase of rock mass, and is mainly controlled by the interval of interlayer cracks. SONG Zhichen et al.[32]’s research on two parallel-jointed bedding rock slopes shows that the stability of the slope is affected by the angle relationship between the steep-dip joint and the gentle-dip joint. ZHOU Jin et al. [33] successively analyzed the factors affecting the dynamic stability of layered rock slopes, and found that slope height, slope angle, cohesion of structure surface, friction angle of structure surface, bulk density of rock mass, dip angle of rock layer, thickness of layer, length of structure surface, friction angle and cohesion of rock layer all have different effects on dynamic stability of rock mass.

3. Failure Mode of Layered Rock Slope

The structure of rock mass has significant influence on the stability of layered rock slope under seismic action. According to the dip angle of rock layer, this paper divides the layered rock slope into three types: horizontal, bedding and anti-dip layered rock slope. From this perspective, the failure mode of layered rock slope is summarized and analyzed.

3.1. Horizontal Layered Rock Slope

The shaking table model test of HOU Hongjuan et al.[34] shows that the deformation and failure of horizontal layered slope under seismic action are mainly tensile-shear slip failure. Soft rock slopes have significant horizontal tension and shear effects, and an obvious crush zone is formed in the middle of the slope; The deformation and failure of the hard rock slope is later than that of the soft rock slope, which is mainly caused by vertical tensile compression and is accompanied by a large number of rock mass caving phenomena. ZOU Wei et al. [35] conducted experimental research on horizontal layered rock slope with different lithologic assemblages, and found that the failure of horizontal layered rock slope is controlled by the bedding plane, which mainly occurs at the top, especially near the shoulder of the slope, in the form of tensile crack-shear-slip failure; under the same seismic wave action, the upper soft and lower hard slope is mainly composed of the top rock mass shattering and falling, while the upper hard and lower soft slope is mainly caused by the whole shear dislocation due to the pull-apart of the back edge of the rock layer. HU Xunjian et al.[36] simulate the failure mode of horizontal discontinuous jointed thick layered horizontal rock slope under seismic action, and found that the first failure occurred in the slope rock bridge section, and then the failure occurred between the joints. The main failure types of the slope are collapse-type failure, tensile crack-slip-block dumping mixed failure and tensile crack-horizontal slip mixed failure.

To sum up, the failure of horizontal layered rock slope under seismic action is controlled by bedding plane, and is mainly caused by tensile crack-shear slip failure; the soft rock slope will produce obvious crushing zone, while the hard rock slope will be accompanied by a large number of rock slides; the upper soft and lower hard rock slope is mainly composed of the breaking and sliding of the top rock mass, while the upper hard and lower soft rock slope is mainly caused by the whole shear slip caused by the trailing edge tensile crack; when the slope contains interrupted joints, the rock bridge section is
broken and the joints are gradually penetrated, which results in different damage according to the shape distribution of the joint.

3.2. Bedding Layered Rock Slope
The bedding slope is a widely distributed type of rock slope. The deformation of this kind of slope is mainly controlled by the strata, and its stability is relatively poor. The structural surface tendency of bedding slope is often considered as a disadvantageous factor in engineering, but the instability bedding slope is often difficult to control under seismic action.

LI Meng[37] et al. found that the mid-dip bedding rock slope is mainly controlled by two main structural planes, the slope top rock surface is pulled apart, the dominant structure surface is sheared and deformed, the control structure surface is gradually penetrated, the slide body is sliding, and finally the whole through surface is cut off and sliding down quickly, and the failure mode is tensile crack-slip-shear failure. BIAN Kang et al.[38] study the discontinuous joint rock slope with bedding under seismic action, and found that the dynamic stability and failure mode of the slope under seismic force are controlled by the development characteristics of discontinuous joint with bedding. When the slope body has been decomposed into blocks of different size before the macro-slip occurs, which are composed of discontinuous joints and propagating through cracks, and with the slip of the slope body, the slope continues to decompose into a large number of blocks and move towards the foot of the slope, causing sliding or dumping. FAN Yalun et al.[39] used the shaking table test to find that the bedding slope failed to slide along the discontinuous surface. LI Xianglong et al.[40] used a similar model to make a physical model of the slope to carry out the centrifuge dynamic test, and also found a similar conclusion: the structural surface including secondary joints may undergo tensile fracture, resulting in the disintegration of the rock mass. The research of FAN Gang et al. [41] shows that the failure mode of the bedding rock slope with weak interlayer is mainly manifested by the vertical pull-apart of the back edge of the slope and the shear-slip of the middle and upper weak interlayer along the side slope, and the failure mode of the slope is the pull-slip-caving type. Huang Runqiu et al.[42] through large-scale shaking table test, have shown that the deformation failure of hard rock bedding slope (HD) is usually characterized by bedding slip-lower uplift collapse instability; soft rock bedding slope (SD) is bedding slip-bottom extrusion-layered slip instability.

To sum up, when there is a controlled structural surface in the bedding rock slope under the seismic action, the slope top layer is mainly fractured, then the dominant structural plane is shear deformation and gradually through, and finally the whole rock slope is broken-slip-shear failure along the continuous surface; when there is a discontinuous joint or discontinuous surface, the rock mass is broken before the macro-slip, or sliding along the discontinuous surface, and the failure occurs in the form of pull-slip-caving; the deformation of the hard rock slope is in the form of bedding slip-uplift collapse instability; the soft rock slope is in the form of bedding slip-bottom extrusion-layered slip instability.

3.3. Anti-dip Layered Rock Slope
There is no space for sliding deformation along the bedding plane, so the slope body is relatively stable under seismic action. ZHANG Haina et al. [43] found that the larger the slope angle, the more likely it was to be destroyed by dumping; with the increase of seismic coefficient, the dumping damage gradually changed to slip failure. YANG Guoxiang, et al.[44] used the shaking table model test, and found that the failure mode of the anti-dip layered rock slope is earthquake induced — the loosening deformation of the top and the surface of the slope, the crack development of the structure surface opening the crack of the slope body, the extension and the increase of the interlayer dislocation — the failure of the top and the surface of the slope is aggravated — the extension of the tension crack at the foot of the slope and the increase of the interlayer dislocation, or the phenomenon of block shear, which leads to the large-scale collapse of the slope or the appearance of the arc-shaped through cracks along the slope. LIU Handong et al.[45] through the shaking table test, concluded that under the action of strong earthquake,
the slope surface of the anti-dip layered rock slope is loosened, the middle and lower parts of the slope begin to produce cracks and continue to extend to the interior and upper part of the slope body until the cracks break through and the slope eventually collapses. FAN Yalun et al. [46] through the shaking table test, found that the failure of the anti-dip rock slope is caused by the tensile fracture in the near vertical direction and the shear fracture in the middle and lower part of the slope, resulting in overall instability failure. MA Hongsheng et al.[47] used large-scale shaking table test, and found that the failure of anti-dip rock slope with weak interlayer first appears as slope shoulder falling block, then appears horizontal fissure, then appears longitudinal fissure and intersects with horizontal fissure, and the middle weak interlayer is extruded. The failure mode is the middle strata extrusion slip-out type. FAN Gang et al.[48] through the large-scale shaking table test, concluded that the slope body with muddied interlayer anti-dip rock first appears the local falling block of the slope shoulder, then the slope body slides out along the saturated mud interlayer layer in the middle and upper part, the longitudinal crack appears in the upper part of the slope body and is connected with the horizontal crack, and the top of the slope is crushed.

To sum up, under the seismic action, the anti-dip layered rock slope mainly caused the slope top and the slope surface loose destruction, the slope body crack extension, the interlayer stagger and the slope middle and lower part tension crack development, finally the crack through or slipping damage occurs through penetration. The influence of the weak interlayer on the anti-dip layered slope is mainly manifested in changing the failure path of the slope. The slope is usually plastic extruded along the weak layer, which causes the upper rock mass to stretch out and slide out; when the seismic coefficient, the angle of cut and the degree of soft and hard rock are different, different failure modes such as dumping, sliding and collapse will occur.

4. Research Prospects

The failure mode and stability of layered rock slope under seismic action are affected by the structural characteristics of rock mass, the geological environment of rock mass and the characteristics of ground motion, which is a very complicated problem. Although the predecessors have done a great deal of research and achieved certain results, there are still many problems in the engineering related to the layered rock slope in the complex and fragile geological environment, which need to be further explored:

a. The existing researches are mostly the analysis of the natural state of layered rock slope under seismic action, and seldom involve the influence of rainfall, reservoir water level change, excavation unloading, blasting, etc. Research in this area will be the focus of the future;

b. Under seismic action, the characteristics of layered rock slope not only depend on the properties of rock and joint itself, but also on the combination of them. However, the existing researches on joint fracture distribution and how to consider the influence mechanism of discontinuous joint distribution on slope stability are seldom involved. In addition, it is also an important research direction to consider the deformation mechanism in the first step of the analytical solution.

c. The uncertainty of space and time exists in rock parameters, which makes the conclusion obtained by the deterministic method less reliable. In the future, combining the analysis of layered rock slope under seismic action with artificial intelligence, reliability analysis and other uncertain methods will make the conclusion more scientific.

d. Slope actually occurs in a complex multi-field geological environment. Therefore, the method of analyzing the stability of layered rock slope with multi-field, multi-process and multi-calculation method coupled under seismic action becomes the direction and difficulty of current research, which requires high computing power, but with the development of computer, this direction will be studied more comprehensively.

e. The study of slope stability evaluation under seismic action is limited to homogeneous and simple slopes, but in practical engineering, most of them are made up of non-homogeneous materials, so more complex models should be established to analyze layered rock slopes under seismic action.

f. Rock material is essentially granular material, and its macroscopic mechanical properties depend on microscopic characteristics. There are few methods to study the characteristics of rock particles. At
present, it is necessary to strengthen the understanding and summary of the micro-characteristics of rock slope.

g. The evaluation index of slope stability under seismic action includes safety factor and critical or permanent displacement. We should not only pay attention to the relative rigid safety factor concerned by the engineering circles, but also discuss the relatively flexible deformation part concerned by the scientific research circles. But how to realize the unity of opposites is a difficult problem, which needs to be discussed and explored.

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