

Failure characteristics and its influencing factors of talus-derived rock mass during open-pit mining

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Abstract: The failure characteristic of talus-derived rock mass continues to challenge quantitative hazard assessments in open-pit mining. Physical model test was used to assess the failure modes and mechanisms on talus-derived rock mass. The different types of failure modes of the talus-derived rock mass were introduced and a possible failure mechanism relation between the failure zone and the structure of the talus-derived rock mass was also shown. The physical model test results indicate that the rainfall has significant influence on the stability and failure modes of talus-derived rock mass during open-pit mining. The development of the seepage area caused by rainfall initiates the localized failure in that particular area, and the initiation of localized instability is mainly induced by stress changes concentrated in the seepage area.

Key words: talus-derived rock mass; model test; failure mode; rainfall; open-pit mining

1 Introduction

Talus-derived rock mass is defined as an accumulation of rock debris, formed close to a mountain wall, mainly through many small rockfalls [1]. Prediction of development is very important for open-pit mining in talus-derived rock mass, so several mathematical models have been proposed. The proposed models are for the accumulation of talus-derived rock mass in different ways [2–4]. The models are only useful in talus investigation, and fewer considerations are taken into account on the failure characteristics of talus-derived rock mass during open-pit mining.

Failure behavior of talus-derived rock mass is one of the key problems in the design, construction and operation of open-pit mining, and it is urgent to be solved due to the needs of mining engineering [5]. Talus-derived rock mass is always regarded as a special kind of colluvial deposit containing rock debris and soil, and talus-derived rock mass is very discontinuous, heterogeneous, incompact and with high water content,

which is widely different from the homogeneous and continuous soil or rock medium [6–8]. Moreover, talus-derived rock mass is also different from rock and soil aggregate (RSA) because RSA is composed of soil and rock blocks in small dimensions, but talus-derived rock mass always contains larger rock blocks with dimensions of several meters and even larger.

Many laboratory tests and field monitoring were carried out to study the failure mechanism of discrete materials [9]. FROST et al [10] performed a series of laboratory tests on the shear failure behavior of granular-continuum interfaces. MATSUOKA et al [11–14] developed an in-situ direct shear test apparatus in both small and large dimensions to test the shear failure behavior of several kinds of coarse-grained granular materials including rockfills at different conditions.

Aforementioned tests were focused on the shear behavior of discrete materials by using relatively small samples, and they only considered the local interface behavior. However, the local interface behavior cannot reflect the generally mechanical behavior of large scale

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talus-derived rock mass with rock blocks of large dimension. Unfortunately, up to now, the mechanism and the failure modes of talus-derived rock mass are still unknown, and no experiments were conducted to investigate the failure characteristics of talus-derived rock mass [15–17].

A physical model test was used to study the failure mechanism of talus-derived rock mass under excavation unloading. This potentially represents a significant advance over earlier talus-derived rock mass approaches which did not consider the rainfall-induced talus failure. To demonstrate the sensitivity of talus-derived rock mass structure to model test and analysis results, the influence of different factors on talus-derived rock mass failure behavior is explored in this work. Moreover, displacement distribution under different conditions is also studied.

2 Experimental model of talus-derived rock mass

2.1 Properties of experimental material

Three different materials, namely, mud-stone, sandstone and silty clay soils, were used to construct a number of talus-derived rock mass in this study. In detail, the talus-derived rock mass is composed of sandstone blocks and silty clay, and the bedrock is mudstone. Because their properties are much different from each other, the three main materials are prepared respectively. Based on the similarity theorems and the properties of talus-derived rock mass materials, the parameters of object materials can be determined.

In order to obtain the object materials for mud-stone, sandstone and soil, a large number of samples were prepared with different material combinations, such as

cement, barite powder, sand, plaster and clay. The compressive strength and deformation modulus of model mudstone and sandstone materials were obtained from unconfined compressive strength test. The cohesion and friction angle were obtained from shear strength test. In addition, oedometer test and direct shear strength test were performed to estimate the compression modulus, the cohesion and friction angle of model silty clay. Because the object materials are much more difficult to obtain, then three sorts of optimal model materials were chosen for each material in the test by fuzzy analysis method. Real material, object material and model material properties of rock and soil are listed in Table 1 and Table 2, respectively.

2.2 Model test tank

The experiments were conducted in a metal tank with maximum dimensions of 1.6 m×0.6 m×1.2 m. The top side and front side of the model were open, while other sides were closed and constructed by strong perspex plates with a thickness of 2 cm. The perspex plates were fixed by steel plate with high stiffness to restrict the lateral deformation and keep in a plane strain state during the test. Through the perspex, we can clearly observe the deformation or failure region during the excavation of the talus-derived rock mass.

In order to reduce the boundary influence, the distance from the border of the excavation to the vertical and horizontal boundaries was two times the width of the excavation part. The dimension of the model talus-derived rock mass was determined as 1.6 m in length, 0.5 m in height, and 0.6 m in thickness, respectively, and the simulated grading angle of the talus-derived rock mass was about 20°.

The geometrical ratio of similitude was 1/100

Table 1 Real material, object material and model material properties of rock

Rock	Material	Density/ (g·cm ⁻³)	Compressive strength/MPa	Deformation modulus/GPa	Cohesion/ MPa	Friction angle/(°)
Mudstone	Real material	2.45	21	3.4	3.0	37
	Object material	2.45	0.21	0.034	0.030	37
	Model material	2.49	0.36	0.022	0.121	35.9
Sandstone	Real material	2.55	46	8.0	8.2	43
	Object material	2.55	0.46	0.08	0.082	43
	Model material	2.50	0.76	0.053	0.095	38.8

Table 2 Real material, object material and model material properties of silty clay soil

Material	Initial void ratio	Water content/%	Density/ (g·cm ⁻³)	Cohesion/ kPa	Friction angle/(°)	Modulus of compression/MPa
Real material	0.68	21.8	1.98	50	22.3	5.8
Object material	0.68	21.8	1.98	0.5	22.3	0.058
Model material	0.68	21.8	1.98	0.2	22.8	4.213

corresponding to the model tank. The dimensions of the model talus-derived rock mass are shown in Fig. 1. Based on the similarity theorems for model test, the similarity ratio of density, strain and friction angle was 1.0, and the similarity ratio of strength, stress, cohesion, deformation modulus and compression modulus was 1/100.

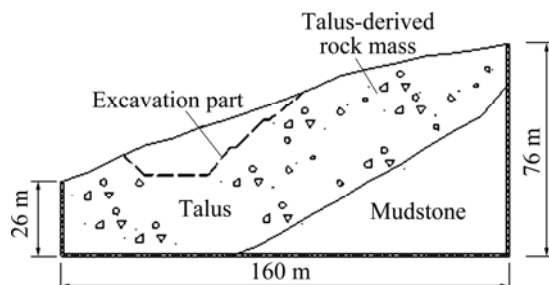


Fig. 1 Test set-up of typical talus-derived rock mass

2.3 Talus-derived rock mass profile and test material placement

In the current study, straight and homogeneous talus-derived rock mass profiles were used in this model test, with the geometry of model rock mass not inhibiting and confining the development of failure surface, as well as the occurrence of talus-derived rock mass failures. The distributions of talus-derived rock mass are wide in the area of the west part of China due to the open-pit mining.

Based on the talus-derived rock mass density and average placement water content, the average dry density of the profiles was then determined and subsequently used to estimate average relative density and void ratio for the test model profile. In addition, the placement water content for the talus-derived rock mass was identical, and the compaction method was used for the model talus-derived rock mass to guarantee the experimental soil to be very densely placed.

2.4 Experimental procedure and measuring system

In the model test, the bedrock of mudstone was prepared first according to the field condition, then sandstone and silty clay model materials were prepared. After the model sandstone was broken into different shapes and dimensions, they were mixed stochastically with soil model material by a composition of 50%. Finally, the mixed talus rock mass model materials were placed into the model tank and the talus-derived rock mass was formed. Silicon grease was also placed smoothly between the talus and the perspex plates to minimize the boundary effect.

The horizontal and vertical displacements on the talus-derived rock mass surface and vertical displacement in the subsurface were monitored by using displacement instruments. The instruments were installed

at different measuring points on the upper side of the talus-derived rock mass in three vertical cross-sections. As shown in Fig. 2, the cross-sections A—A, B—B and C—C were arranged equidistantly in each direction, where X_i ($i=1, 2, 3$) is the horizontal surface displacement measuring points, and Y_{i-j} ($i, j=1, 2, 3$) is the vertical displacement measuring points.

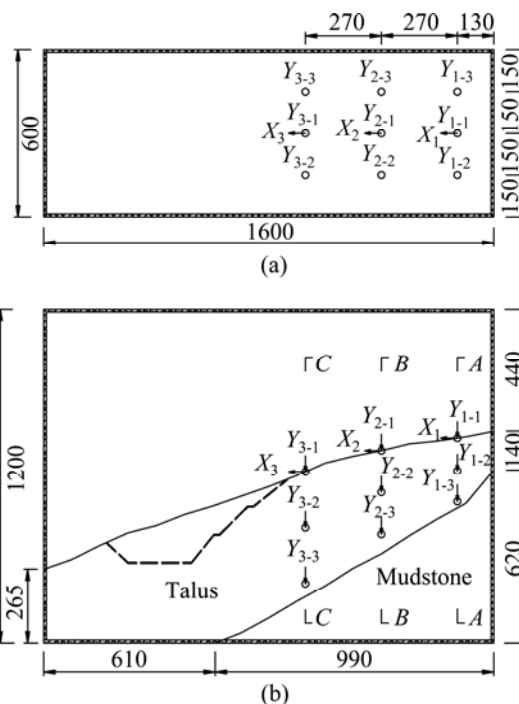


Fig. 2 Measuring arrangement of model test (unit: mm): (a) Planform; (b) Elevation view

In order to induce the change in volumetric moisture content and instability in the talus-derived rock mass model, a rainfall simulator was set at approximately 0.8 m above the model rock mass to produce the effective rainfall intensity. With respect to the water supply and the fluctuation of water pressure, the amount of water flowing into the sprayer arms was carefully controlled, and monitored through a flow meter to maintain rainfall at the prescribed intensity. Moreover, the simulation of excavation was carried out step by step according to the test requirement.

3 Results of model tests

Figures 3–11 show the failure mechanisms/modes of the physical models after excavation unloading. As indicated in Fig. 5, it is clear that the failure modes obtained by physical model test coincide quite well with the traditional real-life conditions, and the structure of talus-derived rock mass plays a vital role in the failure modes during slope excavations. Note that tests do not allow observing the influence of dilatancy on the rock mass behavior in this study. The modes of failure

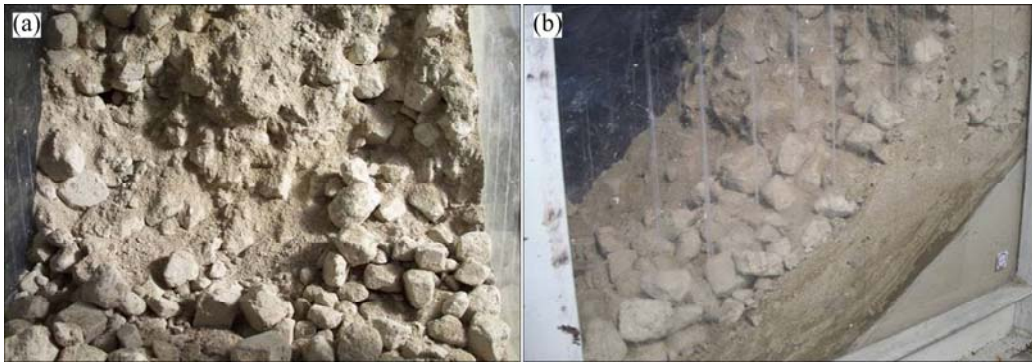


Fig. 3 Failure photographs of framework talus-derived rock mass (no rainfall): (a) Front; (b) Side



Fig. 4 Failure modes of framework talus-derived rock mass (rainfall): (a) Local slip collapse; (b) Large area of slump



Fig. 5 Failure modes of filling-type talus-derived rock mass (no rainfall): (a) Front; (b) Side



Fig. 6 Failure modes of filling-type talus-derived rock mass (rainfall): (a) Deformation development; (b) Slope toe sliding



Fig. 7 Failure modes of suspension talus-derived rock mass (no rainfall): (a) Front; (b) Side

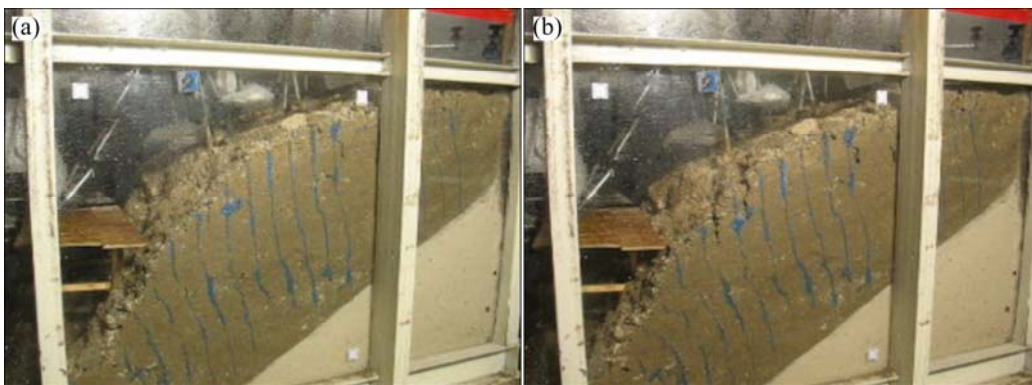


Fig. 8 Failure modes of suspension talus-derived rock mass (rainfall): (a) Cracks appearing; (b) Cracks expanding



Fig. 9 Failure mode of soil talus-derived rock mass (no rainfall): (a) Front; (b) Side



Fig. 10 Failure mode of soil talus-derived rock mass (rainfall): (a) Cracks appearing; (b) Cracks expanding

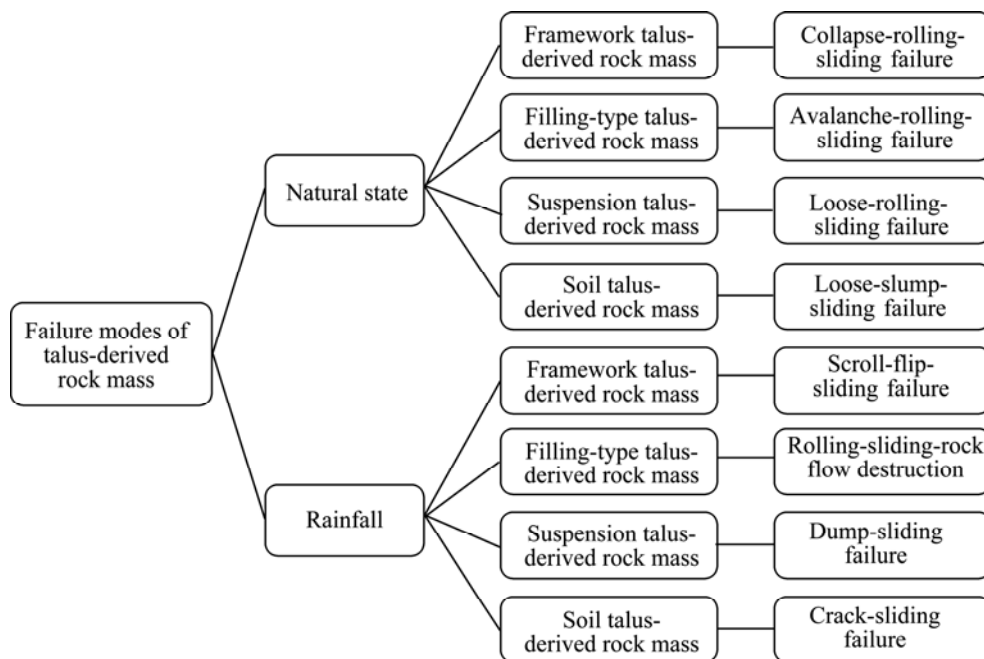


Fig. 11 Failure modes of talus-derived rock mass

observed in all the experiments were summarized based on different talus-derived rock mass types. In general, model talus-derived rock mass in all the experiments failed by shallow noncircular sliding, involving a large portion of talus or localized soil mass near the excavation surface. This general failure mode is consistent with that characterizing the rainfall-induced failures of natural or manmade excavation conditions.

Based on the model test results, the failure modes and mechanisms can be observed according to different types of talus-derived rock mass. In general, model talus-derived rock mass in all the experiments failed by shallow noncircular sliding, involving a large portion of soil mass and isolated rock stones near the excavation surface. Moreover, to a considerable extent, the rainfall or hydraulic conductivity of the talus-derived rock mass structure controlled failure modes and the extent of failures.

3.1 Type 1: framework talus-derived rock mass

Framework talus-derived rock mass is made of block stones as the basic composition of the skeleton. These block stones are contacted directly by point, line or surface. The water content is low. Clay or silt cannot fill the overhead gap between the stones. Due to the great void, under the historical conditions, a perfect row of the pipe network of discharge systems has been formed in the framework talus-derived rock mass. Rainfall and other groundwater will quickly excrete from the foot of the excavation part or get through into other excavation parts. Underground water content is low and underground water level is generally high.

With respect to the framework talus-derived rock mass under no rainfall condition, after excavation, the failure mode can be classified as rolling and sliding. In detail, the sliding of the key stone or stones from one or several of the local lesser extent causes the chain collapse, which is similar to the “snowball”. Moreover, there is no obvious failure surface or irregular failure surface (Fig. 3).

Based on the model test results, the failure mechanism of framework talus-derived rock mass under no rainfall conditions is as follows.

1) When the framework talus-derived rock mass in stable state is excavated, depending on the rock particle size and portfolio structure, there are three regions as critical region, sub-critical region and stable region existing in the excavation surface of the talus-derived rock mass. Because of the disturbance of the external force, the key stone or stones in the critical region of the talus-derived rock mass would collapse or slide, which will result in steady-state change of the rock mass near the sub-critical region or change of stability in the region, and the formation of new collapsing or sliding rock group. Due to a chain reaction, instability collapse or sliding in a larger context of talus-derived rock mass will be triggered. Meantime, when the upper stones are in the process of downward movement, the kinetic energy is generally increasing. Rock and soil within the region will have a great impact force, and there will be a great degree of disturbance. Then it will cause instability destruction of sub-critical region or stable area through the region of the rock mass. Framework talus-derived rock mass will collapse or slide, and then progressively

enlarge, to the state of “avalanche” similar to the formation of a chain “snowball”.

2) According to the differences between the particle sizes of stones, forms of contact between stones, friction characteristics of the stones, a mixture of soil composition between stones and void, the framework talus-derived rock mass has the characteristics of instability state of diversity and energy dissipation exacerbated.

Because framework talus-derived rock mass is contacted directly by point, line or surface between these block stones, the gravity stress of the talus-derived rock mass generally passes through the point, line or surface between the stones. The natural angle of repose of the stones is large in a relatively dry state, so the sliding range of the talus-derived rock mass caused by the instability of some of the rock mass would not be great relatively. Therefore, the general performance of the destruction of the framework talus-derived rock mass is surface or superficial damaged. Its destruction range is also related to the particle size of stones, the form of contact between the stones, the friction characteristics between the stones, a mixture of soil composition between the stones and the void.

In each model test, talus-derived rock mass failures were induced in the experiment by increasing saturation and water level within the talus-derived rock mass and the influence of rainfall on talus-derived rock mass stability was great. The heavy rainfall was simulated after excavation. The deformation and failure process of the framework talus-derived rock mass under the condition of heavy rainfall is shown in Fig. 4.

Figure 4 shows that the drag force produced by the instability of part of the stones or the loss of the stones mixed with soil causes failure mode of a combination of rock and soil rolling-flip-slide. Under heavy rainfall conditions, failure surface of framework talus-derived rock mass is random and irregular.

3.2 Type 2: filling-type talus-derived rock mass

Filling-type talus-derived rock mass is made of rock and soil to constitute the basic composition of the skeleton. Soil content is large and a lot of internal overhead voids are basically filled by soil. Some areas are the combination of soil, and some are contact regions of stones. Physical and mechanical properties and stability of the talus pile depend on both the rock and its organizational structure and exposure; in turn, they depend on the nature of the fill soil. Especially, because groundwater occurs in the void of filling soils, runoffs slowly, and exists perennially, the nature of talus piles is extensively impacted by groundwater.

Based on the model test, the instability and failure form of filling-type talus-derived rock mass after

excavation in no rainfall state are shown in Fig. 5. Obviously, the failure mode of filling-type talus slope is controlled by the sliding of the key stone or stones, and the sliding of the key stone or stones from small area causes the failure mode of chain collapse as rolling and sliding. Filling-type talus-derived rock mass has no obvious failure surface after destruction.

With respect to the failure mechanism of filling-type talus-derived rock mass, it is noted that when the filling-type talus-derived rock mass in stable state is excavated, there are also some part critical region, sub-critical region and stable region existing in the excavation surface of the talus-derived rock mass. By the disturbance of the external force, the key stone or stones in the critical region of the talus-derived rock mass would collapse or slide, which will result in a steady-state change of the rock mass near the sub-critical region or a change of stability within the region, and the formation of new collapsing or sliding rock group. Due to a chain reaction, instability collapse or decline of the rock pile in the larger context of rock mass will be caused. Meantime, when the upper stones are in the process of downward movement, the kinetic energy is generally increasing. Rock and soil within the region will have a great impact force, and there will be a great degree of disturbance. According to the difference between the particle sizes of stones, the form of contact between stones, the friction characteristics of the stones, a mixture of soil composition between stones and void, the filling-type talus-derived rock mass has the characteristics of instability state of diversity and energy dissipation exacerbated as well.

To consider the influence of rainfall, the deformation and failure processes of the filling-type talus-derived rock mass on the condition of heavy rainfall are shown in Fig. 6. The deformation and failure modes of the filling-type talus-derived rock mass are greatly controlled by the small-scale debris and it flows loss from the foot of the excavation part, leading to the partial destruction, and the failure mode of the rock mass in the upper part as rolling-sliding-rock flowing, and continuous sliding failure frequently. Failure surface is an irregular arbitrary curved sliding surface.

Under heavy rainfall conditions, the failure mechanism of filling-type talus-derived rock mass involves the developing of stable excretory system of underground pipe network, and it plays important roles in controlling the rise of groundwater level and maintaining rock mass stability. Because of the foot rock mass excavation or the heap load of talus-derived rock mass, the original underground water pipe network excretion system would be destroyed, rainfall infiltration would be blocked and the groundwater level would rise, causing the increase of pore water pressure and hydraulic

gradient of rock mass, getting high pore pressure of potential sliding surface or weak layer and affecting the rock pile stability. Under the impact of sustained hydrodynamic force, there would be a small area of debris loss within the talus-derived rock mass toe. When the loss of soil goes to a certain extent, it will undermine the existing transient state of equilibrium. And when the shear strength of rock and soil is no longer great enough to resist the decline force, the talus-derived rock mass sliding failure occurs, as shown in Fig. 8.

3.3 Type 3: suspension talus-derived rock mass

Suspension talus-derived rock mass is made of soil. The water content is great. Large rocks are suspended internally. There are only a few contacts between rocks, or basically no contact. The gap is essentially the soil voids; the overall physical and mechanical properties and stability of talus-derived rock mass depend on the soil. The groundwater of suspension talus-derived rock mass mainly occurs in the gap of filling soil. The runoff is slow and water exists perennially. Therefore, the nature of this kind of talus-derived rock mass is influenced greatly by groundwater.

Figure 7 shows the instability and failure form of suspension talus-derived rock mass after excavation in no rainfall state. The failure mode of suspension talus-derived rock mass is a combination of loosing, rolling and sliding. The failure surface is an irregular curved sliding surface. In no rainfall state, the failure mechanism of suspension talus-derived rock mass involves stress releases in the excavation toe. If the excavation part of the talus-derived rock mass reaches a certain gradient, the sliding force is greater than the resistance force, and then overall sliding happens.

Considering the heavy rainfall condition, the deformation and failure modes of the suspension talus-derived rock mass are slide-sliding. In detail, the suspension talus-derived rock mass dumps in early dislocation, and then develops to slide-sliding failure. Failure surface of suspension talus-derived rock mass is a combination of sliding surface of broken line and irregular arc. As for this kind of talus-derived rock mass, when the soils slide gets along with the weak side or potential damage face, if there are higher strength sliding stones, the sliding stones would be avoided, and the irregular sliding surface is formed, as shown in Fig. 8.

Under heavy rainfall condition, it is noted that the failure mechanism of suspension talus-derived rock mass is creep-dumping-shear failure. Such landslide has three basic conditions: 1) free-form deformation surface; 2) low tensile strength of the rock mass and soil; and 3) rock and soil materials prone to plastic deformation. The basic skeleton of suspension talus-derived rock mass is soil, which is generally silty clay or clay-based. Tensile

strength of silty clay or clay is generally small. After excavation unloading, if the event of rainfall happens, rainfall infiltration makes matric suction of the talus-derived rock mass non-saturated zone and non-expansive soil reduce, and forms transient saturation of the soil; lower matric suction will lead to the decreasing of shear strength of non-saturated zone and non-expansive soil to reduce, and forms transient saturation of the soil; lower matric suction will lead to the decreasing of shear strength of non-saturated zone of soil. At the same time, a range of the soil in the suspension talus-derived rock mass reaches the plastic flow state due to the infiltration of rainwater. And under the condition of gravity stress and continuous rain infiltration, the rock mass deformation sustainably develops and increases, and intensity gets low. When the deformation of suspension talus-derived rock mass reaches a certain stage, the upper soils of this kind of talus-derived rock mass gradually dump and fold along the tensile cracks, resulting in producing new fissure on the back of the creep zone edge and inducing new creep-dumping-shear failure.

3.4 Type 4: soil talus-derived rock mass

The skeleton of the soil talus-derived rock mass is made of soil. The water content is also great. A large number of small stones exist interiorly, which can be classified as the general gravelly soil. The overall physical and mechanical properties and stability of the talus-derived rock mass depend on the soil.

Based on the model test results, the failure mode of soil talus-derived rock mass after excavation is loose-slump-sliding failure and the failure surface is an irregular sliding arc surface. In detail, after the foot of the talus-derived rock mass is excavated, the stress is released. When the excavation reaches a certain gradient, the rock mass of the sliding force is greater than resistance force, and then, overall sliding happens the (Fig. 9).

The deformation and failure processes of the soil talus-derived rock mass on the condition of heavy rainfall are shown in Fig. 10. The deformation and failure modes of the soil talus-derived rock mass are cracking-sliding failure; from the crack dislocation of the initial upper rock mass into the late tension and shear destruction, the destructed sliding surface is an arc-shaped sliding surface.

The deformation and failure processes of the soil talus-derived rock mass under the condition of heavy rainfall are very inconsistent with landslide displacement and plastic distribution of slip along the sliding surface. Landslide, which gets along the sliding state of the sliding surface, is uneven. Therefore, landslide would deform and disintegrate easily. It would produce

micro-cracks and the tension cracks, which are more conducive for rainwater infiltration. After excavating the soil talus-derived rock mass toe and rain falling, the upper surface of the rock mass firstly produces tension cracks due to the deformation of talus-derived rock mass, and expands gradually with the development of deformation. The stress state within the rock mass is the shear state. With the gradual accumulation of elastic-plastic strain of the talus pile rock mass, the back tensile fracture surface and front shear crack surface get through each other. Then the first sliding occurs. And then, the upper and lower parts of the talus-derived rock mass start to have traction sliding following the second and third block due to the lack of supporting after the sliding of the lower landslide. Overall, the failure type of soil talus-derived rock mass is shear failure. The failure type of slip wall and posterior margin is tension subsidence damage, while the leading edge segment is destroyed by the way of over thrusting or loading.

By comparison of model test results, different types of talus-derived rock mass failure modes are obtained and summarized in Fig. 11.

It is obvious that rainfall has a great impact on the stability and failure modes of talus-derived rock mass. The formation mechanism of sliding caused by rainfall is that the infiltration of rain destroys the stress equilibrium system of rock mass. The main impacts of water infiltration on the talus-derived rock mass are: 1) the matric suction of the talus-derived rock mass reduces; 2) rainfall erodes the talus-derived rock mass; 3) rainfall soaks to soften the talus-derived rock mass; and 4) groundwater is recharged by rainfall.

In addition, as for suspension talus-derived rock mass and soil talus-derived rock mass, the formation of sliding surface always has the characteristics of progressive destruction, which means that this kind of talus-derived rock mass deformation develops slowly in the beginning, and when the excavation unloading deformation accumulates to a certain extent, the weakest resistant surface of the rock mass will suddenly link up to form the failure.

4 Conclusions

1) Physical model tests for evaluating the effects of the structure of different types of talus-derived rock mass on its failure mode and mechanism after excavation unloading were carried out in laboratory. The test results indicate that the rainfall has significant influence on the failure characteristics of talus-derived rock mass. In general, the rainfall seems significantly affect the failure mode and the failure zones of talus-derived rock mass. In addition, excavation unloading process of the talus-derived rock mass has a light effect on the stability

of the natural talus-derived rock mass.

2) Different types of talus-derived rock mass failure modes were introduced, and a possible failure mechanism relation between the failure zone and the structure of the talus-derived rock mass was also shown. Especially, the rainfall has a great impact on the stability and failure modes of talus-derived rock mass. The development of the seepage area caused by rainfall initiates the localized failure in that particular area, and the initiation of localized instability is mainly induced by stress changes concentrated in the seepage area.

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露天矿开采中岩堆体的破坏特征和影响因素

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摘要: 在岩堆体露天矿开采过程中, 岩堆体的破坏特征一直是国内外风险量化分析的巨大挑战。通过物理模型试验研究露天矿开采岩堆体的破坏模式和机理, 分析不同类型岩堆体的破坏模式和可能的破坏机理, 以及破坏区与岩堆体结构特征的关系。结果表明: 降雨对露天矿岩堆体的稳定性和破坏模式有重要影响, 降雨首先在岩堆体的某个薄弱区域诱发渗流而产生局部失稳, 这种失稳主要是由渗流区域的应力集中而引起的。

关键词: 岩堆体; 模型试验; 破坏模式; 降雨; 露天矿

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