



Study on deformation and failure law of soft-hard rock interbedding toppling slope base on similar test

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Abstract

The phenomenon of toppling deformation and failure is ubiquitous in layered anti-dip rock slope. In this paper, the development process of toppling deformation and failure is simulated by similar tests. In the test, the rock test model of soft-hard interbedding is established by the law of similarity. Based on the test results, the process of soft-hard interbedded rock toppling deformation is simulated, and six stages (five stages in actual) of the toppling process are summarized. The characteristics in each stage are described, respectively. The relationship between displacement-time and stress-strain in the process of deformation is systematically analyzed and studied. Besides, numerical simulation tests are carried out by using the three-dimensional discrete element software 3DEC to consider the effects of different lithologic ratios on the toppling deformation and failure modes. The influence of joints on the toppling deformation is also considered, which corresponds to the characteristics of the toppling deformation before and after the occurrence of cracks.

Keywords Toppling deformation · Similarity test · Numerical simulation · 3DEC

Introduction

Toppling deformation is one of the most common failures in rock layered slope. It is widely existing in the fields of hydro-power station, mining, transportation, and urban construction, which may cause many catastrophic accidents, such as the instability accident of the Brilliant artificial excavating slope in the USA, the rock mass collapse accident of the Ghurgar anti-dip toppling slope in Peru, the instability failure of the sandy conglomerate slope in the Jinchuan open-pit mine in China, and the phosphorus mine failure of Yanchi River in China (284 deaths) (Tan et al. 2009). These geological disasters caused by toppling deformation have brought casualties and property losses.

In some large-scale hydropower projects in China, there are a large number of slope toppling deformation and failure phenomena in rock slope. These toppled and deformed rock masses have brought difficulties and additional treatment costs to the construction of hydropower stations. The formation mechanism and deformation law of the toppling rock slope, as well as the stability problem, affect the safe operation of hydropower stations. It is necessary to systematically analyze this kind of deformation, including summarizing its genetic mechanism and development characteristics.

Toppling failure is a typical instability form of layered rock slope, which mostly develops in anti-dip layered rock slope. The study of toppling rock slope began in the 1950s. Talobra et al. first noticed the phenomenon of toppling in rock slope with a reverse layered structure (Talobra 1957), and described this phenomenon in detail. Subsequently, Muller et al. studied the relationship between toppling and landslides (Muller 1968). However, till the early 1970s, toppling deformation was formally proposed as a model of slope deformation (Frettas and Watters 1973); especially, Goodman and Bray did a systematic study on the types of toppling deformation of layered slopes (Goodman and Bray 1976), which aroused extensive attention of geotechnical engineering circles to the toppling deformation of rock mass. They classified the

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toppling deformation into three types: flexural, blocky, and blocky-flexural toppling. To clarify the forming mechanism of toppling, many scholars discussed the forming process and mechanism of toppling based on kinematic analysis by using physical simulation tests and numerical simulation (Bukovansky et al. 1976; Wyllie 1980; Evans 1981; Wang 1981; Teme and West 1983). In addition to numerical simulation methods, laboratory experimental research was also used by many scholars to analyze the development mechanism of toppling. Adhikary and Dyskin revealed the mechanism of flexural toppling failure with joints by using centrifugal tests with brittle and plastic material models (Adhikary 1995, Adhikary et al. 1996, 1997). The first analytical approach for flexural toppling was proposed by Aydan and Kawamoto, who incorporated the bending cantilever concept into a calculation model (Aydan and Kawamoto 1992). Zuo et al. found that the main form of deformation and failure of anti-dip slope is fracture failure through a physical and mechanical model test, and used “composite cantilever beam” to describe the characteristics of toppling deformation and failure (Zuo et al. 2005). Alzo’ubi studied the effect of tensile strength on toppling deformation through similar tests of centrifuges (Alzo’ubi et al. 2010). He believed that flexural toppling failure in rock slopes contains a single set of steeply dipping discontinuities (Alzo’ubi 2009). Yeung and Thurairajah (2011) studied the change in the rule of slope toppling deformation characteristics with the change in friction angle, displacement, and other factors through the base friction test (Yeung and Thurairajah 2011). Chen et al. (2015) compared the results of centrifuge simulation tilting deformation test and numerical simulation. The results showed that the continuum discrete element-based method (CDEM) and discontinuous deformation method (DDA) were effective in dealing with the problem of toppled rock mass with rock bridges (Chen et al. 2015).

At present, the main research methods on the toppling slope include physical experiment method and numerical simulation method. Previous tests mostly use simple physical models to study the mechanical mechanism of toppling. The lithology of the toppled rock mass is mostly neglected, and homogeneous rock mass is only considered in the tests. However, in practical engineering cases, the rock slopes with toppling deformation are mostly soft-hard interbedded.

In this paper, laboratory models of soft and hard interbedded rock mass with different lithology are prepared by using similar materials. The loading simulation test is carried out to simulate the development process of soft-hard interbedded toppling rock by using a laboratory test instrument designed independently by the authors’ research group. The rationality of the test results is verified by numerical simulation using the

three-dimensional discrete element software 3DEC. The development law of toppling deformation is also analyzed and studied by using 3DEC (Itasca Consulting Group Inc. 2007).

Laboratory similarity test

This paper based on the foundation of Zhongnan Engineering Corporation Limited, Changsha, China, and combined with the engineering example of the left abutment slope of the Miaowei Hydropower Station on Lancang River in China. The slope is a soft-hard interbedded toppling deformed rock slope with a lithologic ratio of metamorphic sandstone and slate of 1:1. The size ratio of the model to the actual slope is 1:100, and similar materials are prepared according to the similarity principle. The hard rock model selected in the test is mainly based on metamorphic sandstone and sandstone, while the soft rock model is based on slate and phyllite.

The ratio of similar materials used in hard rock is barite fix/quartz sand/gypsum/cement/water = 28:28:27:3:15. The ratio of similar materials in soft rock is barite fix/quartz sand/gypsum/glycerol/water = 40:40:14:1:7 (Jiang 2017). The parameters of the model material are shown in Table 1. The shape of the model is shown in Fig. 1. The model is built according to the soft-hard interbedding, and monitoring points are placed on the rock slabs of different positions and different lithologies to monitor deformation and displacement.

Test result

Test phenomenon

The horizontal length of the whole model is 130 cm, the thickness of a single layer is 5 cm, and the width is 20 cm. The height of the model from left to right (from loading side) is gradually decreased from 90 to 30 cm.

The model includes two kinds of materials, which simulate soft rock and hard rock. The two lithologic models are arranged alternately to simulate the soft-hard interbedding model with ratio 1:1. The model is built and placed in the instrument for 24 h to make the model self-stable, and the load is applied horizontally by stages. The loading curve is shown in Fig. 2. According to the characteristics of deformation and failure during the test, the test process is divided into six stages.

Stage 1: Closure of rock stratum

This stage is the preparatory stage before the test. Although the slab has been polished as far as possible before the model is built, the surface of the slab is still rough and not completely closed due to the limitations of manufacturing technology,

Table 1 Model parameters

Rock mass	Model		Actual rock mass		Joint	Bedding surface	Structural plane
	Soft rock	Hard rock	Soft rock	Hard rock			
Density ρ (kN/m ³)	25	27.2	25	27.2	Normal stiffness JKN (Pa/m)	6.6×10^9	5×10^9
Bulk modulus (E/MPa)	240	1500	1450	9000	Shear stiffness JKS (Pa/m)	1.25×10^9	1.1×10^9
Poisson ratio	0.31	0.27	0.31	0.27	Cohesion c (kPa)	51	48
Cohesion c (kPa)	90	220	530	1300	Friction angle ($^\circ$)	22	20
Friction angle ($^\circ$)	33	52	38.7	53			

errors in the construction process, and disturbances in the layout of monitoring points. There are still some gaps between the layers of the model, as shown in Fig. 3. In this stage, the model slab is not deformed during horizontal compression, and the displacement is mainly caused by the closure of inter-layer clearance. In this stage, the horizontal load pressure is from 0 to 1.5 MPa.

Stage 2: Creeping of rock mass

When the gaps between layers are completely closed, the load is continued. Firstly, the main deformation is the flexible deformation of the soft rock. Compression deformation is dominant at the bottom, and flexural deformation occurs in the upper strata due to the existence of an empty surface. Because the deformation of hard rock is very small, hard rock strata between soft rock limit the space for deformation of soft rock. Therefore, the flexural caused by flexible deformation is not very obvious.

Stage 3: Crack initiation

With the continuous application of external loads, tensile cracks occur on the tensioned side of hard rock, but the cracks

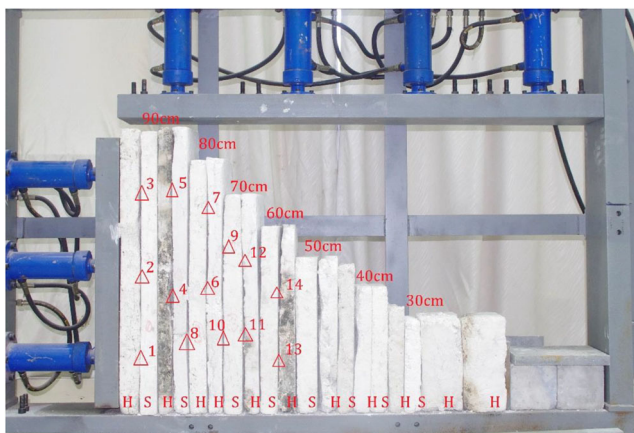


Fig. 1 Model of tests, H—hard rock; S—soft rock. Red triangle—monitoring points

do not open and penetrate. The occurrence of cracks is nearly horizontal and vertical to the rock stratum. The crack develops from one side of the tension deformation, that is, the loading side to the other side, shown in Fig. 4.

Stage 4: Crack penetration and opening

Cracks continue to develop from one side of tensile failure to the other side, resulting in a penetrating crack. According to the statistics of crack location, three groups of crack penetration planes may be connected in the model, and these three groups of penetration planes are the three failure planes in the final failure model. Cracks in both soft and hard rocks are opened. The open cracks are triangular. It is difficult for hard rock to produce obvious plastic flexural deformation. Affected by the tension cracks, the hard rock is cut into rectangular blocks, shown in Fig. 5.

Stage 5: Breaking

In this stage, the internal cracks of the slab are fully opened, and the fracture rock mass in the upper part of

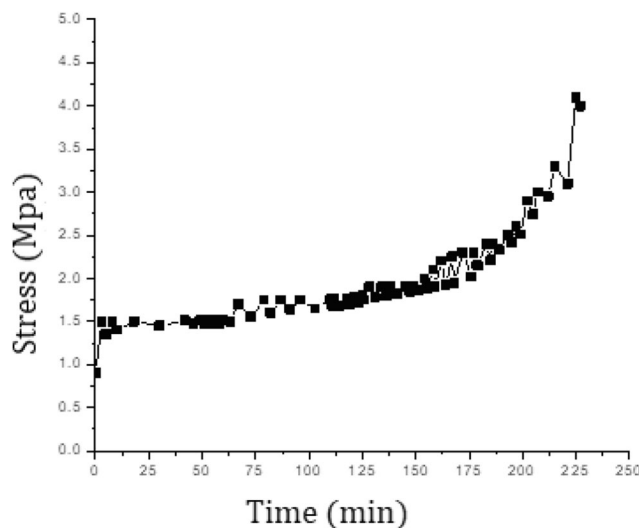


Fig. 2 Loading curve

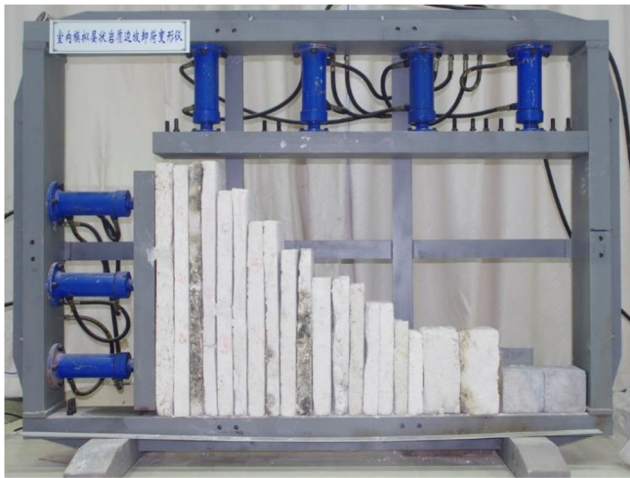


Fig. 3 Creep stage

the slab are separated from the rock mass at the bottom, forming an anti-dip state. When the rock mass at the bottom are extruded, it will deform toward both sides. The rock mass breaks up and loses support to the upper rock mass, which makes the upper rock slab bend toward the free surface. Soft rocks are relatively fragmented, and some slabs are broken into many blocks, shown in Fig. 6.

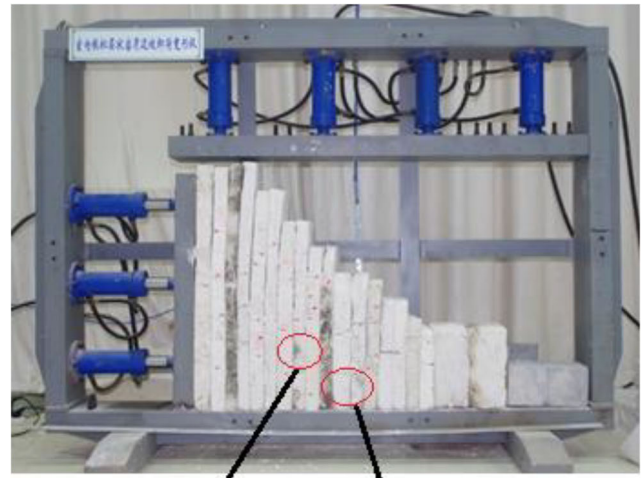


Fig. 5 Crack penetration and opening stage

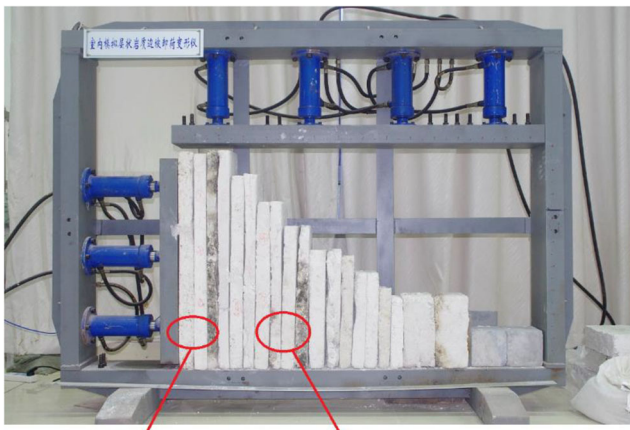


Fig. 4 Crack initiation stage and non-through cracks

Stage 6: The final failure

The rock slabs at the bottom of the model are compressed and fractured by horizontal loads, and lose supporting effect on the upper rock mass. The upper rock masses have been completely destroyed, and lost original rock formations. Some slab dip



Fig. 6 Breaking stage



Fig. 7 The final failure stage

angles are nearly horizontal. Cracks occur in deep slabs, but the deformation space is limited, shown in Fig. 7.

Analysis of test results

Analysis of displacement-time curve

The displacement results of the test are processed by photo processing software to read the photo data of different stages. A group of continuous photographs is taken during the test. The pixel coordinates of the marked points in the photographs are read by the photo processing software. The pixel coordinates of different marked points in a group of photos are counted from top to bottom, and the ratio of the pixels to the real displacement is obtained by converting the scale of the photos to the pixels. Statistical data of each photo point are imported into the graph processing software to generate point curves for comparison and data analysis. The displacement-time curve is shown in Fig. 8.

Through the analysis of the displacement-time curve, the following rules can be obtained.

- (1). The trend of the curve reflects several stages of the test deformation. In the initial stage of the test, the gaps between the slabs are compressed and closed, and the deformation rate is high. The deformation is close to linear, and the time is about 0–5 min. Then, the deformation is the creeping deformation stage, which is the flexural creep deformation of rock stratum and compression deformation of bottom rock stratum. The deformation curve is also close to a straight line, and the time is about 5–20 min. With the loading, the hard rock stratum first produces tiny cracks until it penetrates. Creep deformation is still dominant in soft rock strata, and tiny cracks are gradually formed. Hard rock restricts the deformation space of soft rock between hard rock layers, so the overall deformation trend is slowing down, and the time is about 20 to 100 min. Continuous loading makes the cracks open, flexural failure occurs in a short time, and the overall displacement increases sharply. The time is about 100 to 140 min. Finally, rock toppling failure occurred.
- (2). Deformation curves of different positions in the same stratum are quite different. The deformation law of the same stratum in the early stage of deformation is the same. After the crack occurs, the upper stratum have enough space for deformation and development due to the better condition of facing space, and the deformation is larger after the crack opens. The lower rock mass correspond to the deep rock mass embedded in the actual slope, which have lacking deformation space and little overall deformation, result in no obvious opening of cracks and mainly compressive deformation.
- (3). The displacement curves of different strata are different. The displacement of hard rock stratum is smaller than that of soft rock stratum in the creeping stage. Hard rock strata restrict the deformation and development of soft rock strata. Cracks and fracture deformation first occur in hard rock. The whole deformation of soft rock strata is relatively gentle. The flexural and compression

Fig. 8 Displacement-time curve of test monitoring points

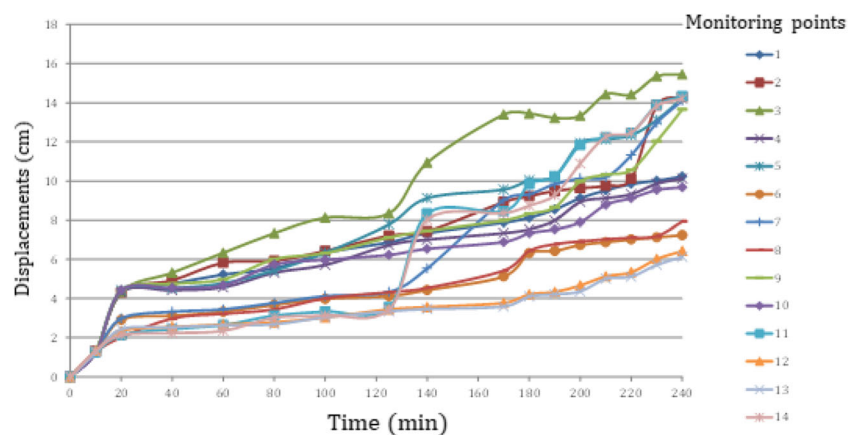
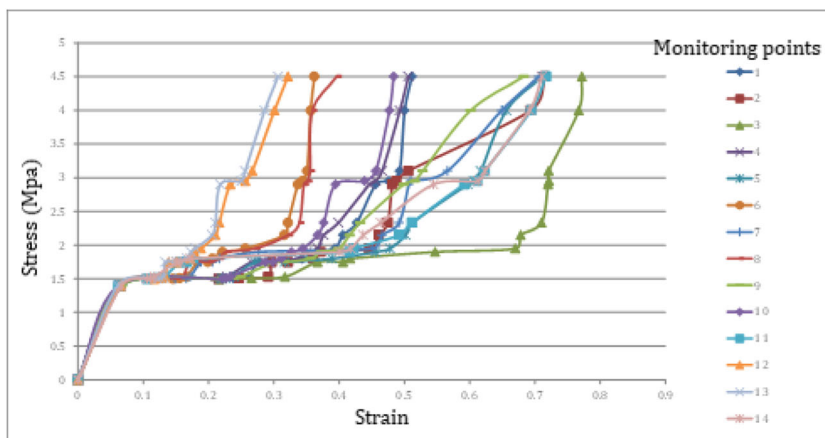


Fig. 9 Stress-strain curve of test monitoring points



deformation is the main deformation in the early stage, accompanied by fracture deformation. In the later stage of deformation, although the rock mass breaks, the whole rock masses are relatively complete, which still have a certain supporting effect on the whole slope.

Stress-strain analysis

According to the stress-strain recording instrument, the stress-strain relationship of each monitoring point during the test is recorded, and the stress-strain curves are obtained, shown in Fig. 9. According to the stress-strain curve, the following rules can be summarized.

(1) The deformation law of the stress-strain curves is the same in all parts of the strata. The early stage is creep deformation, and the deformation curve shows that rock mass is instantaneous elastic deformation and viscous deformation with time increasing. It shows the viscoelastic deformation characteristics of creep deformation. After that, the stress-strain curves bend downward due to the tiny closed cracks. Then, the curves bend upward and the strain change rates are faster, which are the result

of the cracks opening. The deformation caused by the rock cracks opening in this stage is irreversible, which reflects the plastic deformation properties of rock mass deformation. When the rock mass finally fails, the broken rock mass loses its connection with the rock stratum. At this time, the horizontal loading has little effect on its deformation change. Before the accelerating stage of strain increases, cracks are generated and not yet opened, so the strain increases slowly.

- (2) Because of the interbedding of soft rock and hard rock, the deformation trends of different strata are the same, but the change rates are quite different. The elastic deformation stage of soft rock is longer and the slope of the soft rock curve is smaller. Hard rock enters the plastic deformation stage earlier; the slope of hard rock curve is larger, and the curve is steeper.
- (3) The pre-deformation curves of rock mass in the same stratum are the same. In the later stage of crack generation, compression deformation is the main deformation in the deep rock mass, and no large failure deformation occurs after the cracks or local deformation occurs.

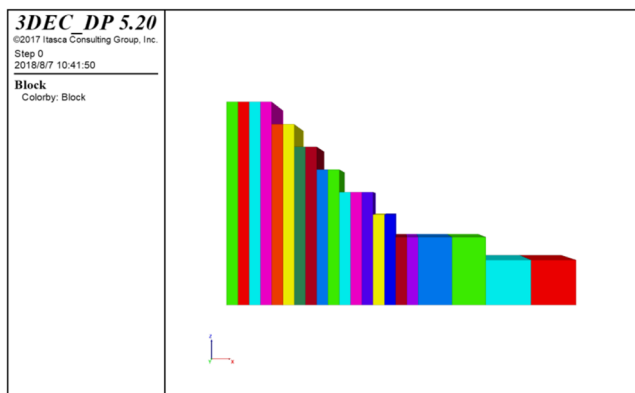


Fig. 10 Geometric model

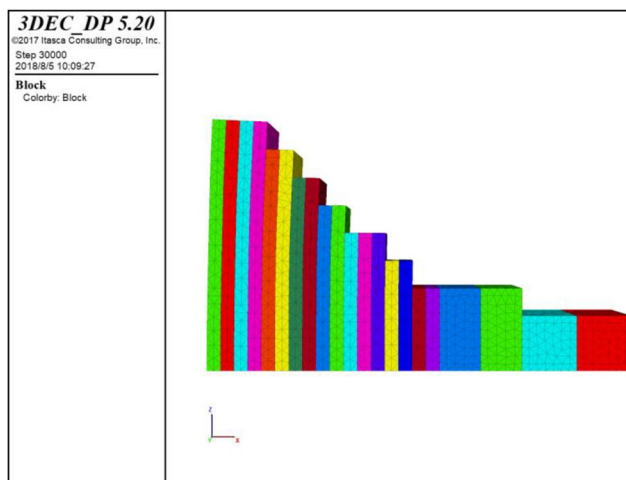


Fig. 11 Creep stage

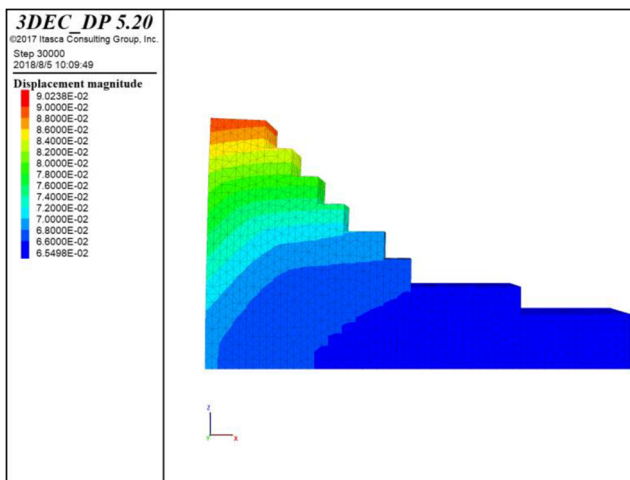


Fig. 12 Displacement distribution of creep stage

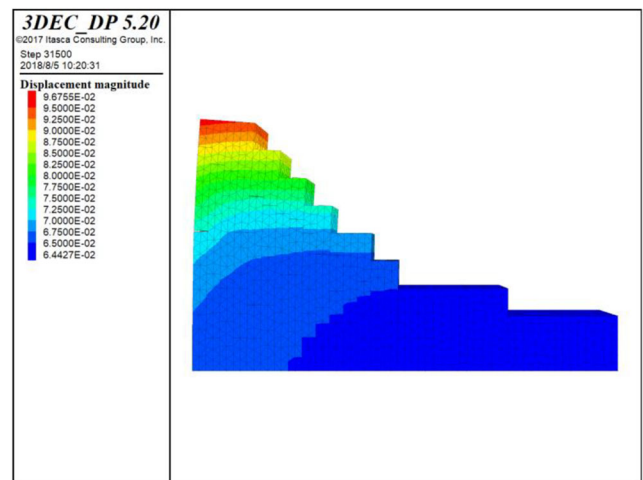


Fig. 14 Displacement distribution of crack initiation stage/crack penetration and opening stage

Numerical simulation of toppling test

Introduction of numerical analysis method

In order to verify the rationality of the toppling test results, the paper uses the discrete element software 3DEC5.2 developed by Itasca Company to carry out numerical simulation tests. The discrete element method (DEM) can simulate the effect of the interface and joints on the deformation of rock mass very well.

Numerical simulation analysis of the toppling test

The numerical model is built according to the ratio 1:1 of the actual test model. It is 90 cm high, 150 cm long, and 20 cm wide. The model is shown in Fig. 10. According to the Cartesian coordinate system, the horizontal direction along the slope of the model is X-axis positive direction, the Y-

axis is pointed inward along the direction of the strata, and the Z-axis is vertical in direction.

The boundary conditions of numerical simulation are set according to the loading mode and the boundary conditions of the physical test. A 2-MPa horizontal load is applied to the left side of the model. The displacement in the X direction is 0 cm on the right side. The displacement in the Y direction is 0 cm on both sides of the model. The boundary in the upper part is the free boundary. The displacement in the Z direction is 0 cm on the bottom.

The model material corresponds to the actual material. Model material and joint material parameters are shown in Table 1. The rock mass is set to the Mohr-Coulomb model of elastic plasticity. The bedding surfaces and structural planes are set as the Coulomb slip model.

Stage 1 Because the numerical simulation test eliminates the technological errors in the process of making and building the physical test model, the rock surface is smooth. So the model

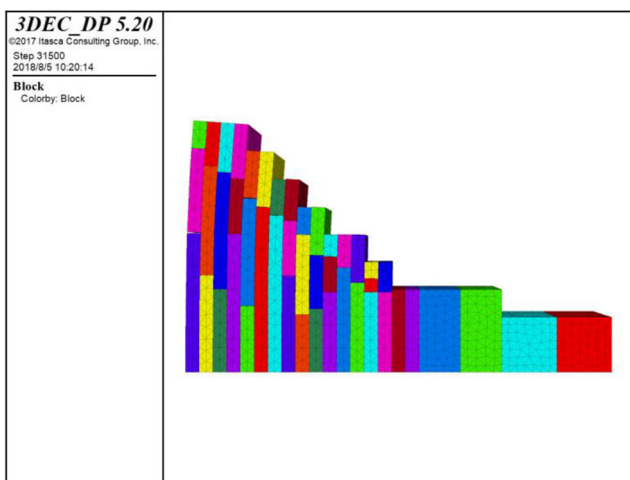


Fig. 13 Crack initiation stage/crack penetration and opening stage

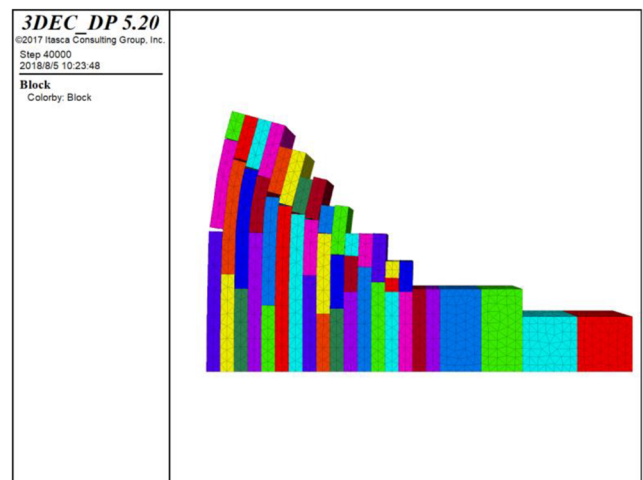


Fig. 15 Breaking stage

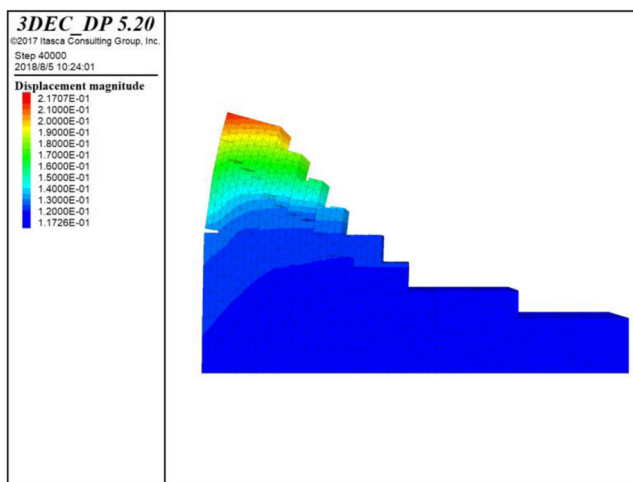


Fig. 16 Displacement distribution of breaking stage

built by numerical simulation meets the requirement of closure. The completion of the model meets the first stage of the toppling test.

Stage 2 At the initial stage of numerical model analysis, 20,000 steps are iterated, and the flexural creep deformation of soft rock is dominant under gravity and horizontal loads. The rock strata have obvious flexural deformation from left to right. At this time, hard rock restricts the deformation of the whole rock mass and makes the overall flexural deformation displacement smaller. As shown in Fig. 11. Deformation displacement is the same as that in the second stage of physical test, and the deformation model of rock strata without joints in the first stage of the test is simulated. The displacement decreases from top to bottom and from left to right. The maximum displacement is located at the top of the slope, which is about 0.09 m, shown in Fig. 12.

Stages 3 and 4 Horizontal joints perpendicular to bedding surfaces are generated during physical tests in this stage.

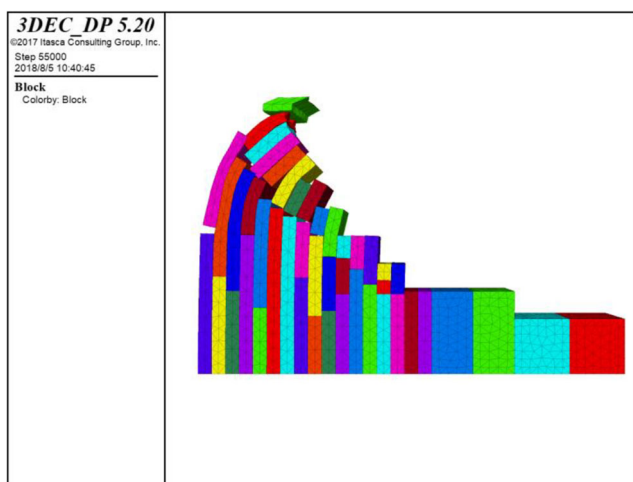


Fig. 17 The final failure stage

According to the statistical results of joint development in the laboratory test model at this stage, the developed joints are added to the model. The further deformation of rock mass occurs after 10,000 steps of iteration. The main deformation mode of the rock mass is flexural-block toppling deformation due to the existence of cracks and the opening of cracks. The rock mass has clockwise toppling deformation based on the right endpoint of the joint. The joints open triangularly from the left side. A group of through joints forms a step-like near-linear fracture surface. This fracture surface is the potential fracture in the final failure model, shown in Fig. 13. The maximum displacement is about 0.096 m. Due to the influence of dead weight and horizontal load, the top displacement is relatively large, as shown in Fig. 14.

Stage 5 The calculation iterates to about 40,000 steps, and the top joints' surface is opened, forming a more obvious fracture zone. The slope deforms along the fracture zone, and the horizontal joints open in a triangular shape. The dip angles of the top strata change obviously, from the original occurrence upright to the dip angle of 75–85°. There has been an obvious phenomenon of toppling deformation, as shown in Fig. 15. At this stage, the broken hard rock has lost support to the upper rock mass. However, part of the soft rock without fracture is still in the stage of flexible toppling, which restricts the deformation of the upper rock mass. In this stage, the displacement of rock mass at the top of the strata increases sharply, as shown in Fig. 16, with the maximum displacement of about 0.21 m.

Stage 6 In this stage, the model iterates 60,000 steps, and the cracks in the top rock mass are completely opened and the rock strata are completely destroyed. The dip angles of some strata are less than 30°, and some strata are near horizontal or reversed. The broken surface of the rock stratum runs through to form a failure surface of an approximate straight line. The roof rock mass has good deformation space conditions and has

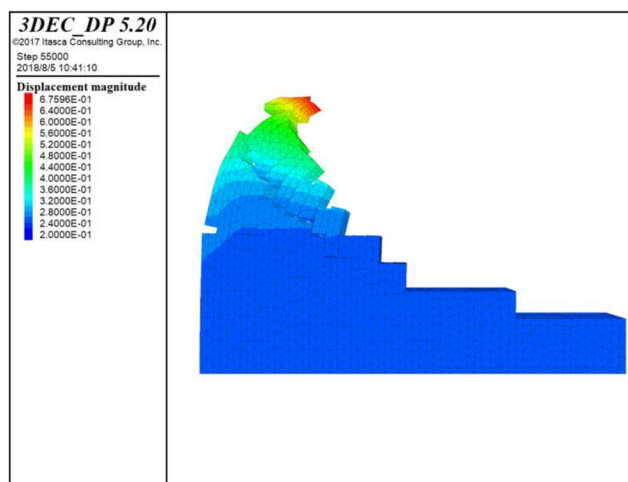


Fig. 18 Displacement distribution of the final failure stage

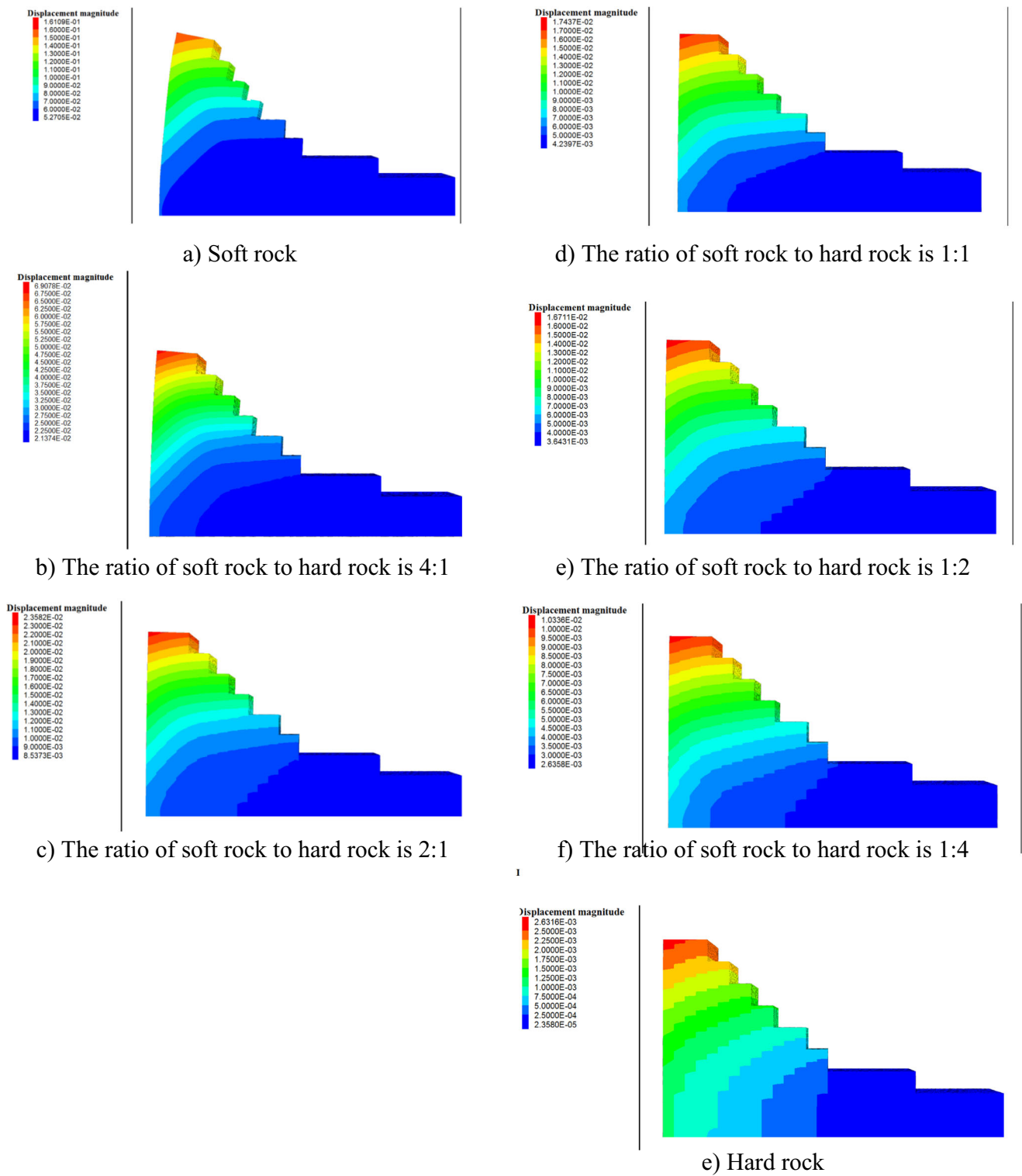


Fig. 19 Iterative 10,000-step displacement distribution of rock mass with different lithologic ratios. **a** Soft rock. **b** The ratio of soft rock to hard rock is 4:1. **c** The ratio of soft rock to hard rock is 2:1. **d** The ratio of soft rock to

hard rock is 1:1. **e** The ratio of soft rock to hard rock is 1:2. **f** The ratio of soft rock to hard rock is 1:4. **g** Hard rock

Table 2 Statistical table for calculating displacement of non-jointed rock mass with different lithologic ratios (cm)

Iterative steps	5000	10,000	15,000	20,000	25,000
Soft rock	12.3	16.1	18.2	20.3	24.3
S/H = 4:1	2.13	6.92	9.72	12.4	18.3
S/H = 2:1	1.54	2.34	5.23	7.82	10.3
S/H = 1:1	1.32	1.74	2.12	3.42	5.23
S/H = 1:2	0.93	1.67	1.93	2.43	4.35
S/H = 1:4	0.75	1.01	1.63	1.98	3.23
Hard rock	0.13	0.26	0.34	0.56	0.74

H hard rock, *S* soft rock

been destroyed. The cracks of the rock mass at the bottom are not open and the deformation is not obvious, as shown in Figs. 17 and 18.

Analysis of hard-soft lithology ratio

The variable analysis is carried out by numerical simulation to consider the influence of lithology. On the basis of the lithologic ratio of soft rock to hard rock 1:1, the lithology of soft rock and hard rock and the different ratios of soft rock to hard rock (4:1, 2:1, 1:2, 1:4) are analyzed. The influence of lithology at different stages on toppling deformation is analyzed. Two cases, jointed and non-jointed, are set up respectively.

Without joints

This kind of situation occurs in the initial stage of rock mass deformation, and there is no tension joint in rock mass. Flexible deformation of rock mass is mainly toppling deformation, which corresponds to the slow creep stage of the rock stratum in an actual situation. Different lithologic ratios are set up to compare the displacement changes with different iterations. The displacement distributions of 10,000 steps of different lithologic ratio test models are simulated by software as shown in Fig. 19. The numerical results are shown in Table 2 and Fig. 20. Before cracks occur, the deformation of rock

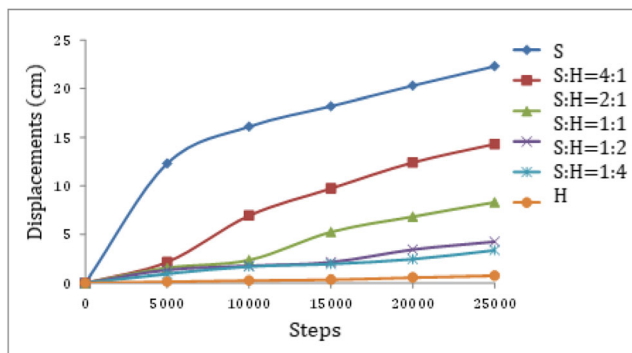


Fig. 20 Displacement trend of rock mass with different lithological ratio

mass is flexible toppling, and the displacement depends on the content of soft rock. The higher the content of soft rock, the larger the deformation. Hard rock in the interbeds restricts the development of deformation, and high content of hard rock has little deformation.

With joints

When the rock mass deformation develops to a certain stage during the test, the rock mass produces cracks. According to the location of the cracks in the physical test, cracks are added in the model. The deformation and failure law of rock mass after crack development are simulated. Taking the ratio of soft rock to hard rock 4:1 and 1:4 as examples, the different failure modes and displacement changes with the same iteration steps are compared.

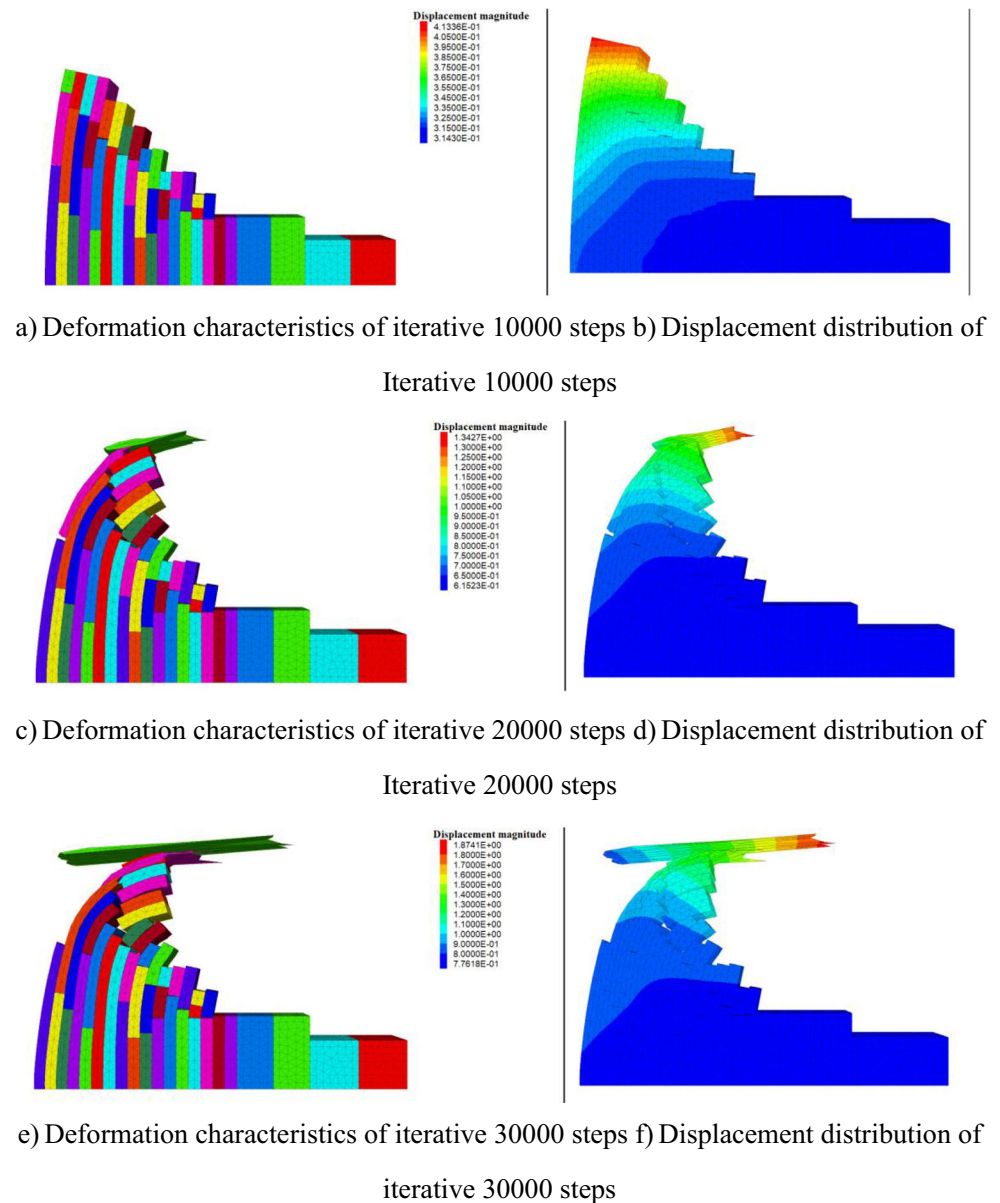
When the ratio of hard rock to soft rock is 4:1, soft rock is dominant, and flexural deformation is dominant in the strata. At the initial stage of deformation, cracks developed at the top also show signs of opening, but the opening degree is relatively small. The rock mass has an obvious extension and flexible deformation. Although cracks are developed, the main mode of rock mass toppling deformation is flexural toppling deformation. The deformation of rock mass at the top of the rock mass is more severe in the later stage of failure. Flexible deformation is dominant in the deep rock mass. The toppling deformation characteristics and displacement distribution of each stage are shown in Fig. 21.

When the ratio of hard rock to soft rock is 1:4, hard rock is dominant, and brittle deformation is dominant in the strata. The cracks developed at the top are also opened, and the toppling rock mass rotates at the turning point of the toppling side. Flexible toppling deformation exists but is not obvious. In the later stage of failure, the top rock mass deformation is mainly caused by the separation or shedding of rock blocks. The phenomenon of toppling deformation in the deep rock mass is not obvious. The toppling deformation characteristics and displacement distribution of each stage are shown in Fig. 22.

Conclusions

In this paper, a similarity test is used to study the process of deformation, development, and failure of soft-hard interbedded toppling deformed rock mass. According to the similarity ratio, two kinds of material models of soft rock and hard rock are prepared, and the indoor model of soft-hard interbedded rock slope is built in the laboratory test. The test process is the process of toppling of vertical strata through external loads. The process of toppling deformation in the test is divided into six stages: closure stage, creeping stage, crack initiation stage, crack penetration,

Fig. 21 The ratio of hard rock to soft rock is 4:1 with cracks. **a** Deformation characteristics of iterative 10,000 steps. **b** Displacement distribution of iterative 10,000 steps. **c** Deformation characteristics of iterative 20,000 steps. **d** Displacement distribution of iterative 20,000 steps. **e** Deformation characteristics of iterative 30,000 steps. **f** Displacement distribution of iterative 30,000 steps

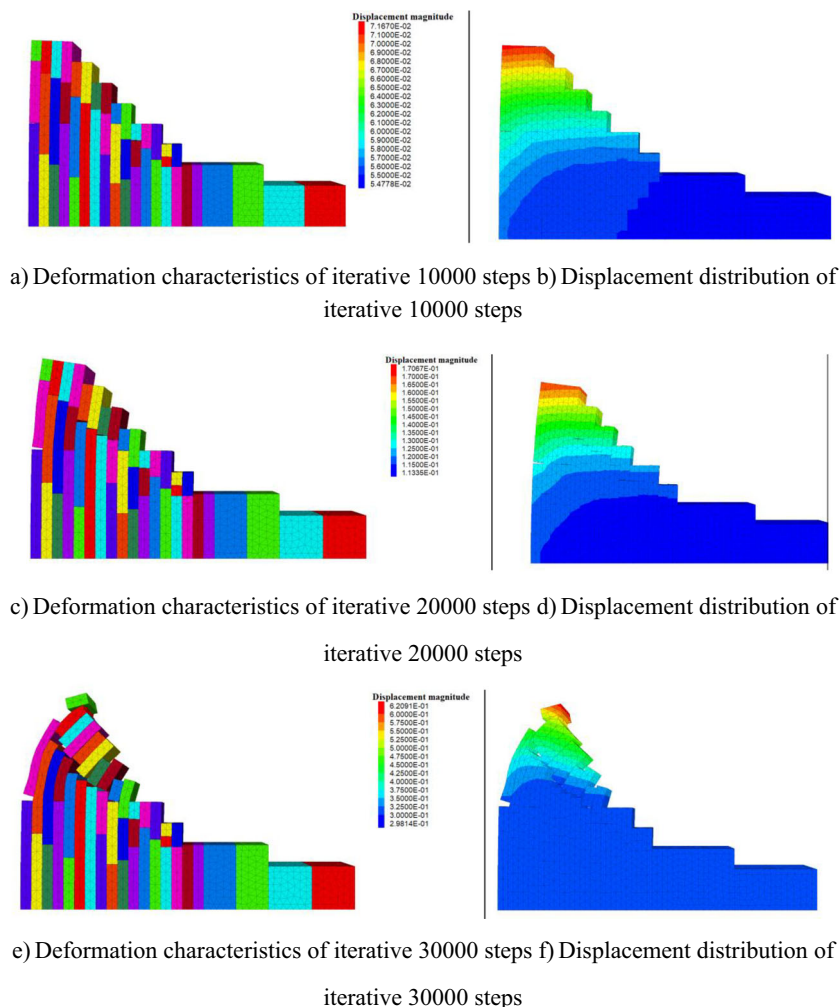


and opening stage, breaking stage, and final failure stage. In addition to the first stage caused by the test technology, the actual rock slope toppling deformation can be divided into five stages. The test results show that flexural creep deformation mainly occurs in soft rock strata at the initial stage of toppling deformation. Hard rock also has flexural elastic deformation in the initial stage, but the deformation is small. Then, soft rock continues to be dominated by flexible deformation, while hard rock first produces cracks due to tension deformation on the bending side. Following the hard rock, tension cracks also occur in soft rock. The crack develops from one side of the pressure to the other side until it penetrates. After penetration, the cracks open at the turning point of the dumping side to form a triangular gap. The rock mass in the upper part of the fracture are

eventually collapsed. At the initial stage of deformation, the deformation of soft rock is relatively large, but the deformation of hard rock is small. The space of soft rock deformation is limited by the hard rock with strong strength, thus restricting the development of the overall deformation. In the later stage of deformation, the hard rock is broken into fragmented blocks, and the soft rock is still relatively complete. The hard rock lose support for the overall deformation, while the soft rock have a certain strength. Soft rock strata are the main supporting factors for rock mass strength in the later stage.

The test process of numerical simulation corresponds to that of the physical test, which verifies the feasibility of indoor test and simulates the development process of toppling deformation. Five stages of the toppling deformation are also obtained by

Fig. 22 The ratio of soft rock to hard rock is 1:4 with cracks. **a** Deformation characteristics of iterative 10,000 steps. **b** Displacement distribution of iterative 10,000 steps. **c** Deformation characteristics of iterative 20,000 steps. **d** Displacement distribution of iterative 20,000 steps. **e** Deformation characteristics of iterative 30,000 steps. **f** Displacement distribution of iterative 30,000 steps



numerical simulation. Through numerical simulation tests, the effects of different soft-hard lithology ratios on the toppling deformation process and the law of toppling failure are analyzed. Before cracks occur, the deformation of rock mass is flexible toppling, and the displacement depends on the content of soft rock. The higher the content of soft rock, the larger the deformation. Hard rock in the interbeds restricts the development of deformation, and high content of hard rock has little deformation.

When joints perpendicular to the rock are formed in the rock stratum, if soft rocks are dominant, the flexural deformation is dominant in the stratum. The rock mass has an obvious extension and flexible deformation. Although cracks are developed, the main mode of rock mass toppling deformation is flexural toppling deformation. The deformation at the top of the rock mass is more severe in the later stage of failure. Flexible deformation is dominant in the deep rock mass. If hard rocks are dominant, the brittle deformation of breaking is dominant in the strata. The cracks developed at the top are also opened, and the toppling rock mass rotates at the turning point of the toppling side.

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