A gravity similitude model for studying steep rock slopes

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Abstract: A method of a large experimental model coupled with a smaller one and an equivalent replacement method are adopted to study the deformation and the failure mechanism of a steep rock slope, in order to solve the difficult problems in space gravity similitude of the experimental model on steep rock slope with weak layers. The experimental results on the Lianziya Precipice of the Yangtze Three Gorges are in general agreement with the field observations. The experimental method adopted is proved to be successful in molding the complex geological condition especially with the weak layers.

Keywords: steep rock slope; gravity analogy; modeling method

1. Introduction

There are many problems about the deformation failure and stability of steep rock slopes which need be solved. Although a lot of work has been done, the results obtained so far are often not in agreement with the information obtained by field monitoring. Since steep rock slopes have usually various types of joints and cracks, and their mechanical models belong to space problems in many situations, it is very difficult to study and solve these complex geological problems, and the proposed remedial scheme is often not based on the correct judgement about the stability of a steep rock slope.

There are two principal problems in stability modeling experiments on steep rock slopes. The first one is that the experiments should be able to simulate human engineering activities and the history of deformation failure of a rock slope. The other one is that the experiments should be able to evaluate and obtain the limit bearing capacity and the safety degree of a rock slope.

Most steep rock slopes including the Lianziya Precipice situated in the Three Gorges of Yangtze River have kept on being impaired by natural and human activities for a long time, nevertheless their present deformation distribution can be still known exactly from among the field monitoring information, which enables verifying the rationality of a model by comparing the deformation results obtained by experiments with the field observations. With the help of experiment results, it is possible to correctly assess the failure mechanism and propose necessary remedial measures.

2. Project description and model design

2.1 Project description

The Lianziya Precipice as shown in Fig.1 is situated on the south bank of the Yangtze River, about 26 km upstream the dam site of the Three Gorges Project. It is a canyon near the exit of the Bingshunbaojian Gorge. The upper and middle parts of the Lianziya Precipice are composed of lower Permian thick bedded limestone intercalated with several weak carbonaceous shale seams, forming a scarf 100 m high. The underlying coal-bearing seams 1.6 m to 4.0 m thick, form a weak basement of the slope even though they are overlying on the massive Huang-Long limestone. The monocline Lianziya strata dip to NW by a dip angle of 26° to 36° and strike to NE by 30° to 50°. The precipice is dissected by 58 deeply-cut wide and long fissures into three zones, with a total volume about 3×10^6 m^3. The volume of the north zone between fissures T_8 and T_{12} is more than 2×10^6 m^3. The front portion of the north zone with a volume of about 5×10^4 m^3 is deformed severely. Its bottom is severely cracked. Toppling failure seems to take place at any time.

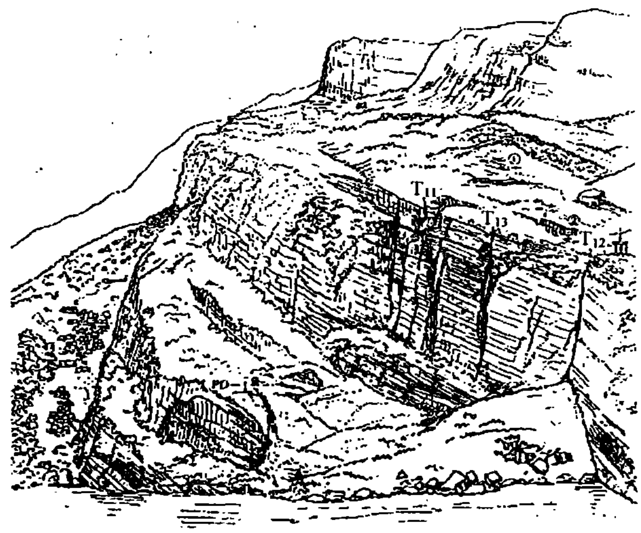

Fig. 1. The geomorphological map of the Lianziya Precipice

Heavy rainfalls and unregulated age-old damaging underground coal mining have greatly amplified the tensile fracturing and resulted in the ground depression

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of the foregoing region. The direction of coal mining is roughly parallel to the strike. It is desirable to use a three-dimensional physical model to simulate the interaction between such complex geological conditions and undermining.

2.2. Development of experimental scheme and model

The precipice is dissected by fissures T_8, T_{12} and other fissures which stretch to the coal seams. There is a thin coating layer above the top surface of the coal seams, which has a very low shear strength and softening property in wet conditions. One of the most important factors affecting the stability of the precipice is the presence of T_{12}. In order to simulate the geotechnical discontinuities such as joints, fissures and weak seams with low shear strength, which control the stability of rock mass, it is necessary to use a large model, but to do such a modeling experiment will cost high and take a long time. Hereby a smaller model is used to explore the feasibility of the experimental scheme and the rationality of the selected parameters before doing the large model experiment to simulate the underground coal mining and backfilling.

The most difficult problem in the large model experiment is how to excavate the coal seams in a three-dimensional model. The slicing method is unsuitable due to the irregularity of coal mining. So, the equivalent replacement method is employed instead.

According to the field survey, the coal mining zone is divided into three subzones which are the simulated objects by the equivalent replacement method. In the equivalent replacement method, the combined parameter of the excavated part of coal seams and the remained part corresponds with the parameter required after mining, and the combined deformation modulus of the designed coal pillars and the coal seams occupied by mining openings is in agreement with the deformation modulus required before mining. The combined deformation modulus is given by the following equation according to equilibrium of forces and equal of deformations.

$$E_0=(E_1A_1+E_2A_2)/(A_1+A_2)$$

where E_1 and A_1 are respectively the deformation modulus and area of the coal seams occupied by coal pillars; E_2 and A_2 are those for mining openings; and E_0 is the combined deformation modulus, i.e. the deformation modulus before mining.

Because the values of the mechanical parameters of the coal seams are too low to find another material having similar properties, the equivalent replacement method is adopted to simulate the resisting slide parameters, the deformation modulus and the compressive strength of the coal seams separately by the various types of materials as shown in Table 1.

There is massive Huang-Long limestone below R_{001}. The stability of the upper rock mass is hardly affected by the gravity of Huang-Long limestone. In order to decrease the total weight of the model, it is necessary to use material with elastic modulus similarity such as gypsum block, to model the massive Huang-Long limestone.

Table 1. Similitude materials and parameters of coal seams

Geological material	Similitude materials and parameters
Oily coating	Similitude for the strength of oily coating: 3 layer of plastic film and talcum. (the cohesion $c\approx0.2$ kPa, the friction angle $\varphi=10°$)
Coal seam	Similitude for the deformation parameter of coal seams: Emulsion (the elastic modulus $E\approx0.45$ MPa) or black foam ($E\approx0.2$ MPa); Similitude for compressive strength of coal seams: Compacted blocks composed of barite and ferric powders (the uniaxial compressive strength $\sigma_c\approx0.25$ Mpa).

Qi Xias limestone is a dominant rock mass between T_8 to T_{12}. The model material used for gravity similarity and elastic modulus similarity is a mixture of barite and ferric powders with gypsum as the cementing agent.

The model embodies R_{001} and 4 other weak layers (R_{201}, R_{203}, R_{301} and R_{401}), and 5 main fissures including T_8, T_9, T_{11}, T_{13} and T_{12}. Other weak layers and fissures except R_{001} were simulated by plastic films. Since the adhesion is much lower, it is especially important to simulate the frictional coefficient. These geologically weak faces can be subjected only to compressive stress and but tensile stress.

3. Model construction and experiment procedure

The smaller model was constituted by a wedge and a backfilled layer carrying T_{12} as the sliding plane of the wedge, on a scale of 1: 400. It had two parts. One was the wedge lying on R_{001} and bounded by R_{001}, T_{12}, T_8, The material of the wedge was a rigid gypsum (E=30GPa). The other part was the pedestal which had the same boundaries as the wedge. The coal seams were positioned on the top of the pedestal and divided into two zones. The elastic modulus of the zone near the Yangtze River was 12 MPa and that near T_8 was 90 MPa.

The goal of the smaller model experiment was to measure the space displacement of the wedge. Totally 5 observation points with micrometer dial gauges were installed to measure 12 displacement components.

The loading procedure of the smaller model experiment was as follows:

a) load by steps to obtain the displacement at each loading step;
b) Repeat the foregoing step with the center of gravity changed slightly;
c) Record the readings every 2 h to observe time-dependent deformation until the deformation is stabilized.
d) Perform stepwise unloading to obtain the displacement at every unloading step.
e) Apply thrust to the model in various direction to obtain the failure load in each direction.

The smaller model experiment gave useful information for the larger model experiment. The stability of the smaller model during loading implied that the larger model could be stable during the development of model or the course of loading. The failure experiment of the smaller model showed that sustained displacement took place when the thrust at NW 10° reached 92 N and that at NE 5° reached only 50 N.

The large model was set up to simulate the underground coal mining and backfilling. Its dimensions were 2.5 m×1.8 m×2.0 m in length, width and height, with a scale of 1: 145. The model embodied 16 mining openings of 70 mm×30 mm in size, which were distributed uniformly, and the direction of mining was the same as that of the strata strike as shown in Fig 2.

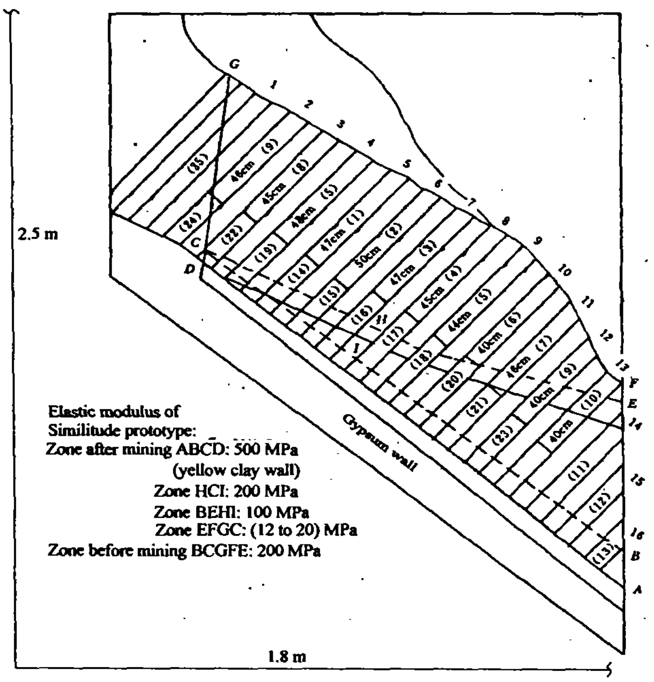

Fig. 2. The section of large model simulating coal seams

Altogether 77 observation points positioned on R_{001} and other weak layers and at the top of the fissures, were employed to measure the strains, horizontal and vertical relative displacements, and opening of fissures therein. In order to monitor the deformation trend when the coal seams were excavated, 10 micrometer dial gauges were installed on the top of the model.

The pedestal of the larger model (Huang Long lime stone) was composed of the precast gypsum blocks cemented by epoxy resin and the precipice model was made of precast blocks cemented partly by a mixture of barite and ferric powders. The large model was shown in Fig.3.

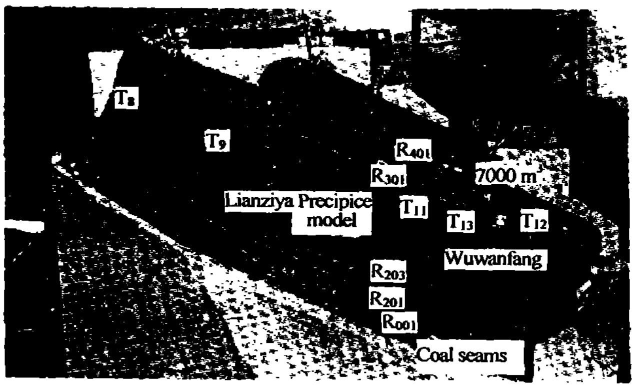

Fig. 3. The model of the Lianziya Precipice

The coal seams were excavated successively. During excavating, the readings of micrometers were monitored to judge whether or not the instability appeared in the progress of deformation. We assumed that a difference of less than 5 % of the total displacement value between two readings suggested the absence of instability and further excavation was allowed. The uphill mining manner was mainly used, with the downhill one adopted at times. The coal seams near the yellow clay wall were hollowed finally.

4. Results and discussion

1. The magnitude and trend of deformation obtained by experiment agree well with those by field observation as listed in Table 2, which suggest that the crucial reasons for the formation of the wide fissures of the Lianziya Precipice are the excavation of the coal seams other than the down deep cutting of the Yangtze River.

Table 2. Openings of T_8 and T_9 in cm

	profile	I - I	II - II	III-III
T_8	model	40.0	62.3	95.7
	field	50.0 to 70.0	80.0 to 105.0	100.0 to 200.0
T_9	model	15.0	56.5	70.4
	field	0.0 to 30.0	30.0 to 50.0	50.0 to 80.0

2. The reason for forming the secondary fissures of the precipice is space twisting and buckling toward the Yangtze River during the excavation of the coal seams. The upper contact surface near the south part of T_{12} is a local tensile failure zone, and It was mainly the high compressive stress on the north part of T_{12} that formed "Wuwanfang" precipice.

3. The low safety factor of rock masses between T_8 to T_{12} have been confirmed by the model experiment, and the most unfavorable direction of thrust is at NW 10°. Further studies should focus on the stability of "Wuwanfang" and on that of the neighboring rock masses in case of unstable "Wuwangfang".

4. The experiment method of combining a smaller model with a larger model has proved the feasibility of the modeling technique and rationality of the chosen parameters.

5. The equivalent replacement method is applicable for tackling problems resulted from chronic irregular coal mining.

6. The similitude model using various types of materials to simulate frictional coefficient, strength and deformation modulus is proved to be successful in studying complex geological conditions especially with weak layers.

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