# Experiment Research of Seismic Failure Model on Soft-Hard Alternant Strata Rock Slope

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**SUMMARY:**
The soft-hard alternant strata rock slope is very typical along the highway from Dujiangyan to Wenchuan, China, where “5.12” Wenchuan Earthquake took place. The investigation of “5.12” Wenchuan Earthquake shows that most of the landslides took place in these areas. However, few studies have been done on the soft-hard alternant strata rock slope stability under seismic condition. This paper presents the 1*g* large shaking table model tests to analyze the instability mechanism of this kind of slope. According to the test, the slope first came out a tension failure at slope shoulder, gradually developed to a shearing failure at the toe, and slided at last when the fracture zones were connected. The failure process was progressive, instead of occurring suddenly. The results also showed a throwing phenomenon on the upper part under the combination of horizontal and vertical shaking, which phenomenon were widely reported in “5.12” Wenchuan Earthquake.

*Keywords: Soft-hard alternant strata rock slope; Physical model; Seismic failure mechanism*

## 1. INTRODUCTION

Soft-hard alternant strata rock slopes are widely distributed in Southwest China, especially in metamorphic rocks areas, red bedrock areas and coal measure stratum. It is more easily to cause landslide, even geological hazards for its weakness, such as its lower elastic modulus and strength, the diversity of weathering degree between soft and hard rock, etc. The deformation and destruction pattern of this kind of slopes are complicated. Now, the collapse and interlayer-gliding phenomenon are serious in the soft-hard alternant strata rock slope, which have been one of the primary problems in highway engineering, especially in seismic conditions (2009). Investigations in “5.12” Wenchuan Earthquake show that the maximum geological disasters density can reach 11.6 place/km along the highway from Dujiangyan to Wenchuan, most of which were taken place in the soft-hard alternant strata rock area (2008).

At present, the stability study of the soft-hard alternant strata rock slope under static condition has been much examined. Zhang Zhuoyuan et al. (1994) has summarized the failure mechanism of rock slope as five geo-mechanics models, those are, creeping and tension type, sliding and fracturing type, bending and tension type, plastic flowing and tension type, sliding and bending type. Wang et al. (2003) described a landslide of a high dip slope caused by Chi-chi earthquake, formed by alternating layers of sandstone and shale separated by interbeds, they pointed out the principal factor caused the instability was the damaging of a thick-bedded sandstone downslope.. Braathen et al. (2004) studied the driving forces and deformation mechanisms of the rock-slope failure in Norwegian, where bedrock lithologies varies from diverse quartzo-feldspatic gneisses, to mechanically weaker schists, phyllites, meta-conglomerates and marbles, among which the earthquake forces is classified as short-term but a main factors to cause the slope slide. Tommasi et al. (2009) described the buckling phenomenon of Lavini di Marco landslide, in Northern Italy, the rocks involved are layered limestones with marly-clayey interbeds. LI Xiaoning et al. (2011) concluded that there were 8 types of deformation and failure modes of the red-bed soft rock slopes in Sichuan, China. Among them, two types (e.g.:

bedding and toppling type, fracturing and collapsing type) were common in the soft and hard sandstone and mudstone interbedded strata slope. Dong Jinyu et al. (2011), in their study of high cutting slope collapse of Three Gorges reservoir area, also classified the failure mechanisms of horizontal soft-hard alternant strata into toppling, sliding, creeping-tension, cantilever-tension and staggered breaking. In general, the failure mechanics of the soft-hard alternant strata rock slope is very complicated and insuffficent. However, few studies are on the soft-hard alternant strata rock slope under dynamic condition, not to mention considering the features of Wenchuan Earthquake, that is, high magnitude, large energy release and long duration. These features lead to a special slope failure phenomenon like throwing, a failure mode reported in the Wenchuan Earthquake investigation.

In this paper, shaking table test results are presented to investigate the seismic deformation characteristics and destruction model of soft-hard alternant strata rock slope, whose prototype is a high and steep slope named Shawozi along the No.213 highway from Dujiangyan to Wenchuan. A tentative discussion is also made to reveal the deformation evolution law of this kind of slopes through the observation of slope model instability process.

## 2. SLOPE MODEL AND PARAMETER SELECTION

### 2.1. Designing of Slope Model

*2.1.1. Prototype of the slope*

Soft-hard alternant strata rock slopes mainly composed of phyllite and limestone are widely distributed along No.213 highway, from Dujiangyan to Wenchuan, China, where "5.12" Wenchuan Earthquake took place. Sha Wozi slope is along this highway where landslide happened frequently. Slope surface is covered by Quaternary colluviums, especially the open-cast mining areas, which is 70 meters below. Slope toe suffers erosions from Minjiang River directly. The counter-tilt slope, with its height over 250m, whose strike/dip are N60°-70°E/SE60°-70° on the upslope and N60°-70°E/SE30°-40°on the down-slope, is relatively gentle on the upper part while steep on the underpart along with fragment rock mass. While the bedding plane, consisting of phyllite and limestone which belongs to Yuelizhai Group of Devonian (Dyl2), strike at N45°~70°E/NW. Limestone is firm and crisp, while phyllite is soft. The zone of phyllite development mainly forms low landforms, like gentle slope and grooves. In general, the slope is soft-hard alternant strata rock like, consist of medium to thick-bedded limestone, limestone with thin layer phyllite , layer phyllite with medium to thick-bedded limestone. (Figure 2.1).

Because the actual slope topography is variant and complicated, the simulation of the slope model was devoted on the feature of soft-hard rock alternant, with the similar shape and gradient as the prototype. The stability study is simplied as plane strain problem.

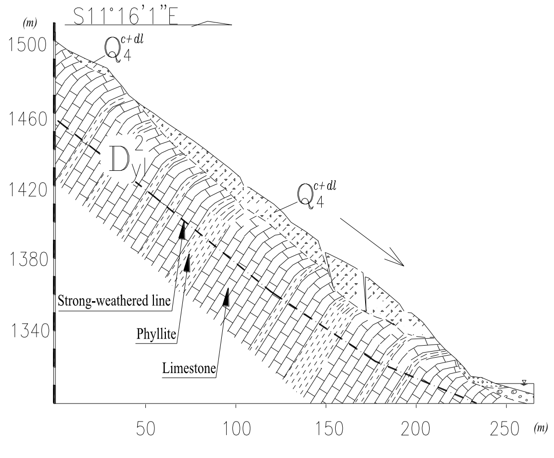


**Figure 2.1.** Engineering geological profile of Shawozi high and steep slope

### *2.1.2 Model sizes and similarity relation*

Similarity designing is one of the key factors for large shaking table test. According to the size of model box, the model height is set to 0.42m which corresponds to a 210m high slope. The geometrical similarity constant λ of model is 500 so that it is one over five hundred of the actual size.

Based on geometric similarity rule, the bottom length ($L_1$) is 0.45m; the top length ($L_2$) is 0.1m; the thickness of slope basement (D) is 0.1m. Limited by the size of model box, the width of model is 0.34m. The dip angle of rock stratum is 57°and slope angle from the top to the bottom is 24°-45°, the same as the prototype slope as shown in Figure 2.2.

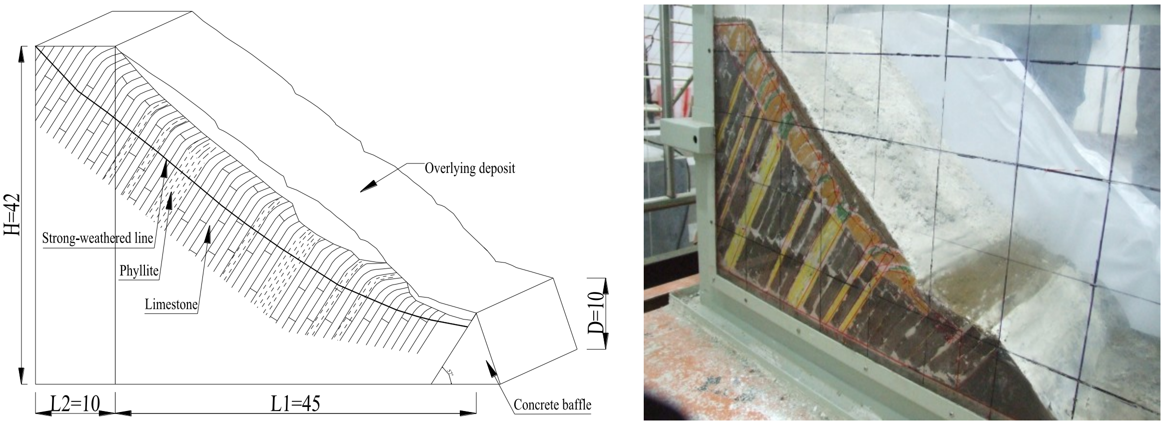


**Figure 2.2.** The sketch and the finished slope model

Refer to the research of Chen et al. (2010), the test keeps a same density of both the model material and the prototype slope. Thus the density similarity constant and acceleration similarity constant is 1. Other physical quantities can be derived from the three constants as shown in Table 2.1.

**Table 2.1.** Similarity Relation in The Model Test

| Physical quantity | Similarity relation | Similarity constant |
|---|---|---|
| Length $l$ | λ | 500 |
| Density | 1 | 1 |
| Acceleration $a$ | 1 | 1 |
| Stress $\sigma$ | λ | 500 |
| Strain $\varepsilon$ | 1 | 1 |
| Modulus of deformation $G$ | λ | 500 |

## 2.2. Selection and Preparation of Model Slope Material

Similar materials are used to keep a same density of the model material and the prototype soil. In order to make the physical and mechanical parameters of test materials meet the similar relationship, as well as being representatively and generally, the proportion of basis material was studied. In this experiment, some common material, like bentonite, barite, quartz sand, gypsum, paraffin oil, engine oil, were used in initial mixture ratio test to make the similar material. After hundreds of direct- shear tests and unconfined compression tests, which was used to measure cohesion, friction angle and deformation modulus of similar material, it turned out that bentonite, barite and paraffin oil have a greater impact on the compounding ratio. So these three kinds of materials were selected as the basic component of the similar materials. The final mass ratio of the component are shown in table 2.2, the similar materials made by which is proved to satisfy of the physical and mechanical similar relationship, as table 2.3 shown.

As there are structural planes and bedding planes in rock, so the model was build by laying small bricks which were made from similarity material, with the size of $10 \times 10 \times 2\text{cm}^3$. The bricks were casting in the foremade moulds as identical to the process of forming concrete cubes. After curing properly, the bricks were placed into shaking chamber to form the model rock stratum. The laying of the bricks should comply with the masonry requirements to avoid connected weak surfaces along vertical or horizontal direction. It is difficult to find a proper similarity material to simulate the structural planes in rock. While structural planes and joints in rock is only several centimeter thick in the prototype, that is, 0.01cm~0.01cm in the model according to the scale factor in the model. In this experiment, quartz sand was filled in the surface between two blocks to simulate the structural planes in the slope model. A layer of 2-3cm thick mountain sand was put on the surface of the model to simulate the Quaternary accumulation. Considering the slope surface is covered with some vegetation which may form a surface shell, a thin layer of gypsum was scattered on the surface of the mountain sand to simulate the shell. Meanwhile, a concrete baffle is placed just in front of the foot-slope to circumscribe the movement of base of the model slope. Two Expanded Polystyrene (EPS) made foam boards, about 10cm thick, were set on the width dimention (one is just behind the slope shoulder) of the model box. EPS is a quakeproof, waterproof and lightweight material, the setting of the two boards aims to decrease the reflection from the edge of model box, while bring negligible weight change to the whole model. The sketch and the finished slope model are both given in Fig. 2.2.

**Table 2.2.** Mass Ratio of Similarity Materials

| Rock/ Mass ratio | Bentonite | Barite | Paraffin oil |
|---|---|---|---|
| Strong-weathered limestone | 70.5 | 12.5 | 17 |
| Weak-weathered limestone | 76.5 | 8 | 15.5 |
| Weak-weathered phyllite | 65 | 13 | 22 |
| Strong-weathered phyllite | 65 | 11 | 24 |

**Table 2.3.** Physical and Mechanical Parameters of Similarity Materials

| Geological prototype | Density/(g.cm$^{-3}$) | Modulus of deformation / GPa | Cohesion/ MPa |
|---|---|---|---|
| Strong-weathered limestone | 2.51 | 0.5-2 | 0.2-1.0 |
| Weak-weathered limestone | 2.61 | 3-5 | 2.5-4.0 |
| Weak-weathered phyllite | 2.32 | 0.3-1.5 | 1.5-3.5 |
| Strong-weathered phyllite | 2.26 | 0.1-0.25 | 0.1-0.5 |
| Ideal material | Density/(g.cm$^{-3}$) | Modulus of deformation / MPa | Cohesion/ MPa |
| Strong-weathered limestone | 2.3-2.6 | 1-4 | 0.2-1.0 |
| Weak-weathered limestone | 2.4-2.7 | 6-10 | 2.5-4.0 |
| Weak-weathered phyllite | 2.15-2.55 | 0.6-3 | 1.5-3.5 |
| Strong-weathered phyllite | 2.1-2.45 | 0.2-0.5 | 0.1-0.51 |
| Similarity materials | Density/(g.cm$^{-3}$) | Modulus of deformation / MPa | Cohesion/ MPa |
| Strong-weathered limestone | 2.34 | 3.81 | 0.83 |
| Weak-weathered limestone | 2.49 | 8.67 | 3.887 |
| Weak-weathered phyllite | 2.15 | 0.76 | 3.1 |
| Strong-weathered phyllite | 2.11 | 0.47 | 0.4 |

## 2.3. Testing Equipment

This experiment was carried out on the shaking table system of the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, ChengDu University of Technology, China.

The testing equipment is a horizontal-vertical 2D shaking table and the size is 1100mm×1100mm. It can provide simple harmonic oscillation and random oscillation in two directions by springs underneath the shaking table. The springs, which are kept in tension state by hydraulic jacks, provide the initial displacement at the start of the test. The initial seismic load is offered by rebound of the springs through removing of the hydraulic jack. The maximum amplitude is 50mm while the maximum frequency is 2Hz under unloaded condition. Hence it can be used to simulate the seismic load. The accelerations in two directions are obtained through acceleration sensors, which are mounted at the center of the table.

The model box is rigid, with steel framework across the width, transparent organic glasses on both long dimention, which is easily to observe the deformation and fracture in the model slope. The size of the box is 1000mm×500mm×700mm. The shaking table system and the model box are shown in Figure 2.3.

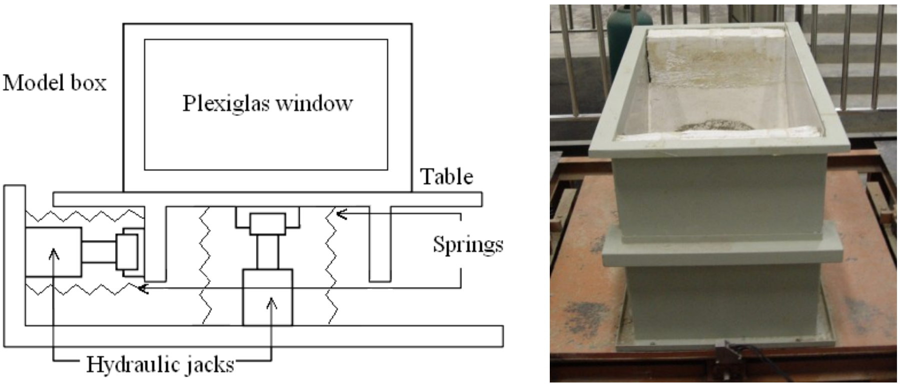
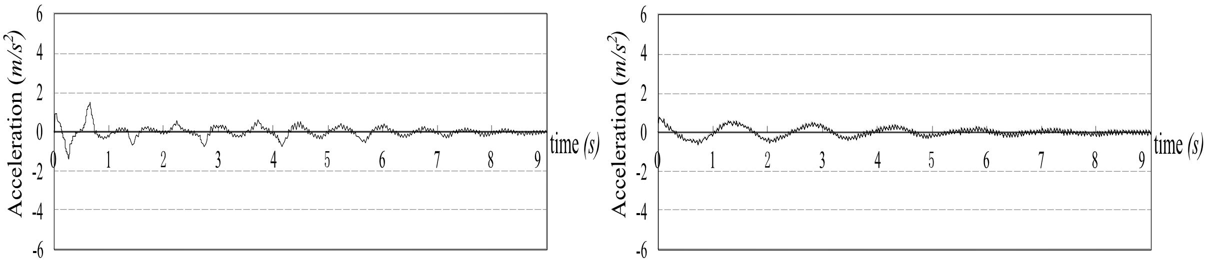


**Figure 2.3.** Shaking table system and model box

## 2.4. Test Procedure

In this study, both horizontal and vertical motions were applied to the table, with initial amplitudes which are 30mm and 50mm for the horizontal and vertical directions respectively. Damped harmonic oscillation waves with a period of 9 seconds were recorded. Accelerations of the shaking table measured by acceleration sensors are shown in Fig. 2.4. There were 15 shakings in the whole test. Each process is recorded by high resolution camera to analyze the micro structure of fracture through the way of playback and slowplay. The displacement of the model is what we concerned, referring to the similar tests, physical observation method is chosen to measure the displacement of the model slope. This method is to set some feature point on the plexiglas window, and measure the distance of initial and final location of the points after each shaking, according to the pre-draw of the slope model.



(a) The horizontal (b) The vertical

**Figure 2.4.** The deformation of model slope in the shaking from side view and top view

## 3. TEST RESULTS AND ANALYSIS

After 15 times shaking, the model slope was totally collapsed and the whole overlying debris fell down along the slip surface. Fig. 3.1 gives the photos of model slope after 11th, 14th, 15th shaking from side and top views, which showed us its deformation and failure process. Along the slope, the observed traces of failure were recorded after each shaking; some typical results are shown in Fig. 3.2.

Within the first 4 shaking, there were no obvious crack on the model surface and both side. In the 5th to 9th shaking, no obvious change happen, besides that a few fragments are thrown out from the top of the slope. After the 10th shaking, a 20cm long 15mm wide (to the maximum) crack occurred on the slope shoulder, close to the plexiglas window side, which was expanding gradually to the other side of the model box during the following 11th to 13th shaking; another 5mm wide crack appeared at the interface between the Quaternary deposits and the base rock on slope shoulder also grew little by little during the 11th to 13th shaking, trending to expend from the shoulder to the slope-foot, as a result, a connected slide surface would come into being soon, as Fig. 3.1 shown. In the 14th shaking, protrusion and cracks can be observed easily in the slope toe, while the crack at the Quaternary deposits-base rock interface had been enlarged from the shoulder to the middle of the slope. Although the cracks haven't run through the slope, most part of the Quaternary deposits had been separated from the base rock, which can be seen clearly from the photo in Fig. 3.1. In the 15th shaking, the model slope broke up immediately, with the Quaternary deposits being thrown forward.

On observation from the tests, few obvious deformations occurred through the whole slope at first. However, once the tensile cracks appeared, the deformation developed rapidly. During the shaking progress, tensile failure and shear failure do not appear at the same time. In fact, the sign of tensile failure takes place first at the shoulder of slope, and the shear failure next at slope toe. The final failure happened when the slide surface became continuous. In a word, tensile cracks firstly emerge at slope shoulder, then the slope-toe began to be sheared, finally the whole slope slides into destroy.

(a) The 11th shaking

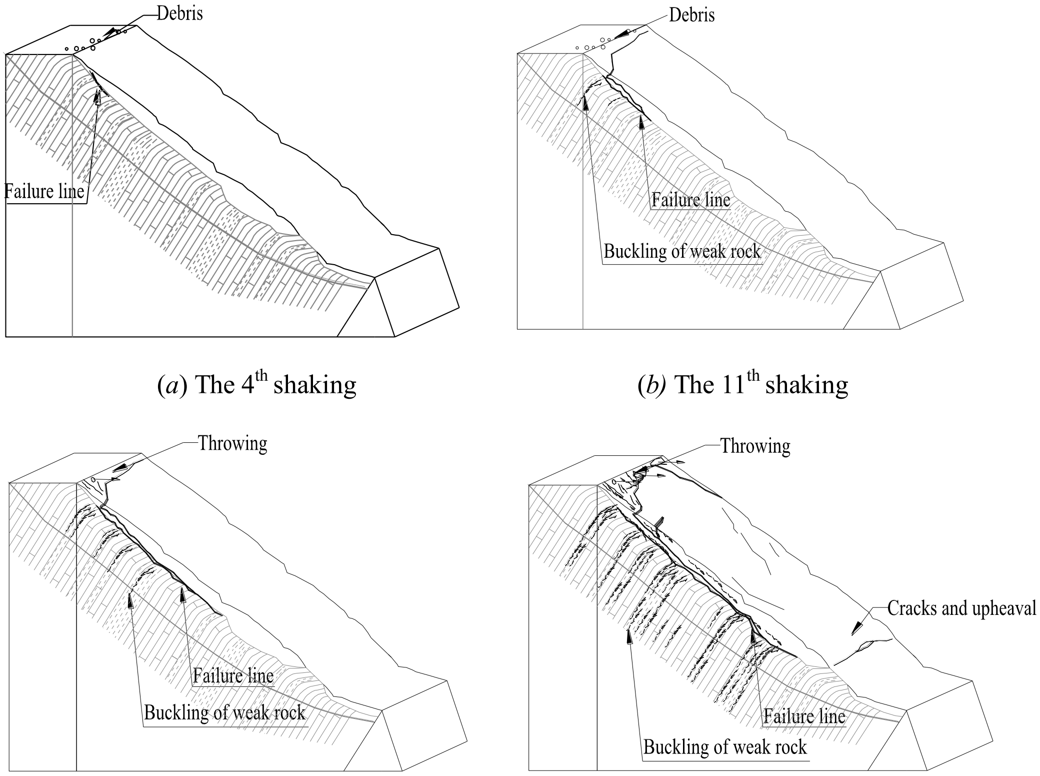
(b) The 14th shaking

(c) The 15th shaking

**Figure 3.1.** The deformation of model slope in the shaking from side view and top view

It can be observed that the weak strata are being compressed by the hard rock in the neighbor, and then extrude outwards in the shaking. Consequently, the shear stress occurred along the interface of soft and hard rock. Further, the tiny tensile cracks gradually grew between in the interface as shown in Fig.

3.2. The rotation of the principal stress induced by the earthquake shearing stress made a toppling tendency of the strata increased during shaking progress.



(*a*) The 4th shaking (*b)* The 11th shaking

(*c*) The 12th shaking (*d*) The 14th shaking

**Figure 3.2.** Failure line of different shaking phases

Throwing phenomenon of detritus on the upper part of the slope was observed for several times in test, which is totally different from fragmentation during rock falls (Nocilla et al. 2009). The movement tracks of them were not rolling down along the surface, but doing parabolas motion. And the sizes of the detritus were ranged from 2mm to 5mm, much smaller compared to the slope. The sketch of the phenomenon is shown in Fig. 3.3. The test reproduced the dynamic behaviors of throwing, the same as the phenomenon reported by Huang et al. (2008) in Wenchuan earthquake, as Fig. 3.4 shown. It was surmised that the special phenomenon was caused by Wenchuan earthquake with high magnitude, large energy and long duration characters. In addition, the magnifying effect of slope existing in seismic condition may explain why the phenomenon happened on the upper part.

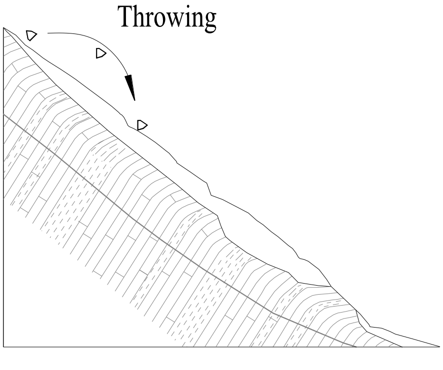


**Figure 3.3.** Sketch of throwing phenomenon

**Figure 3.4.** 300t rock travelled 60m by catapulting had been found on Duwen Road, Yingxu town[12]

Horizontal displacement histories of the Quaternary deposits at different height of the slope were shown in Fig. 3.5. The permanent dynamic deformation developed progressively, once the cracks appear, deformation increases rapidly. It can also found that the tensile cracks first took place at slope shoulder and the deformation developed downwards to the slope-toe under the shaking, which lead to upheaval at slope toe. When the accumulation of deformation turned from quantitative to qualitative change, the failure surface run-through, the slope was completely destroyed. This phenomenon showed us that the slope failure is a progressive process even in seismic condition.

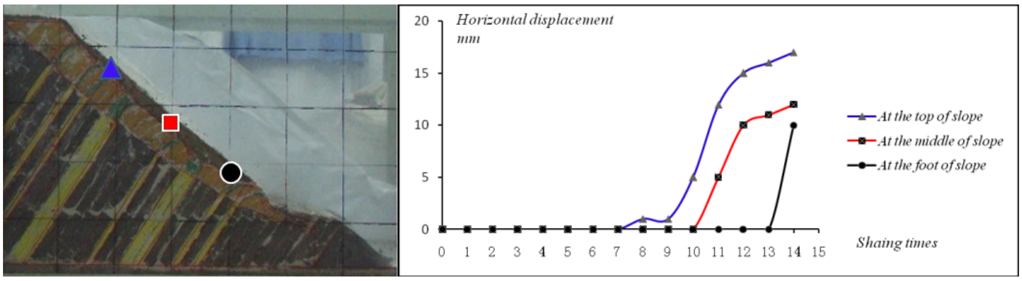


**Figure 3.5.**. Horizontal displacement of the Quaternary deposits at different height of the slope

## 4. CONCLUSIONS

Large-scale shaking table tests were carried out on the soft-hard alternant strata rock slope, which is common in the South east, China:

(i) In soft-hard alternant strata rock slope, tensile cracks firstly emerge at slope shoulder, then the slope-toe began to be sheared, finally the whole slope slides into destroy. In part, the tensile broken and the shear stress together, lead to the final run-through failure surface.

(ii) In this model test, the detritus on upper part of slope presents a dynamic behavior of throwing, which is similar to the phenomenon reported in Wenchuan earthquake, illustrating that there is a throwing trend under the earthquake. Considering it differs from failure modes under static condition, the support measures of slope in earthquake regions with high magnitude should be different from common areas.

(iii) There is time-dependent properties existing in the failure mode of slope even in seismic condition, that is to say, the failure does not occurs suddenly but develops progressively. When the accumulation of deformation turned from quantitative to qualitative change, the failure surface run-through, the slope was completely destroyed.

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