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Dynamic stability of rock slopes and the effect of reinforcement against planar sliding

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ABSTRACT: The authors have been performing some scaled model tests to investigate the response and stability of rock slopes against planar sliding. In these tests, rockbolts/rockanchors are modelled and their reinforcement effect on rock slopes against planar sliding during ground shaking is investigated. These model tests are also used to check the reliability of the numerical simulations. The authors present the outcomes of both model experiments and numerical simulations and compare their implications on actual rock slopes.

1 INTRODUCTION

The response and stability of rock slopes during earthquake are of great concern in relation to transportation facilities, major rock engineering structures such as dams, nuclear power plants and buildings. The recent earthquakes such as 1999 Chi-chi earthquake, 2005 Kashmir earthquake, 2008 Wenchuan earthquake, 2008 Iwate-Miyagi intraplate earthquake and 2014 Gorkha earthquake caused huge damage to transportation facilities, engineering structures and casualties. For example the casualties were more than 4000 people in Beichuan town, which was destroyed by huge rock slope failure from the both sides of the mountain.

The rock mass always contains some structural weakness planes such as faults, bedding planes, fracture zones and joints. These structural weaknesses may lead rock slopes to fail in different modes. One of the common failure forms is planar sliding if the major discontinuity plane daylight on the slope surface. The rock slopes may also contain ground water, which drastically influence the effective stress conditions within the slope. In some cases, rock slopes may be fully immersed within the reservoir of dams or beneath sea surface. When rock slopes are subjected to seismic loads, their stability may be in danger and they may result in their failure.

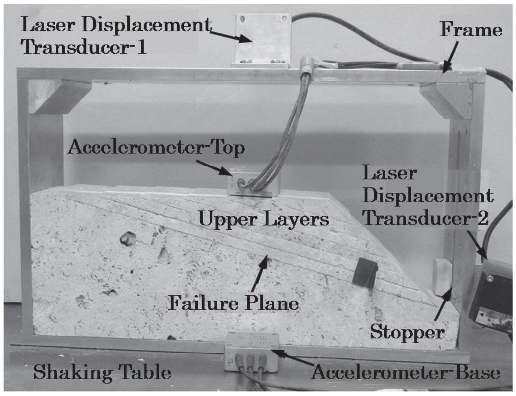
The authors have undertaken an experimental study on the planar sliding mode of rock slopes subjected to gravitational and/or dynamic loads under dry and immersed conditions. Sliding plane of the models tests of rock slopes was inclined at angle of 15 degrees and the material of model slopes was Ryukyu limestone of coral type. The model slopes were subjected to seismic loads under both dry conditions, and the dynamic response of sliding block was observed using laser displacement sensors and accelerometers. In the tests, rockbolts/rockanchors are modelled and their reinforcement effect on rock slopes against planar sliding during ground shaking is investigated. The authors present the outcomes of both model experiments and numerical simulations and compare their implications on actual rock slopes.

2 DEVICES AND MODELS

In order to understand the dynamic response and stability of rock slopes, several shaking table tests on rock slopes with a potentially unstable block on a plane dipping to the valley side shown in Figure 1 were carried out. The shaking table used for model rock slopes under both dry and immersed condition was produced by AKASHI. Figure 1 shows the views of model tests on the shaking tables.

The actual rock slope with a height of 50 m and having a potential plane of failure at an angle of 15 degrees is scaled down to a model with a scale of 1/500. The model material is coral Ryukyu limestone. The input-wave, the acceleration of upper block acceleration and relative displacement of the potentially unstable blocks were measured using accelerometers and laser displacement transducers as shown in Figure 1. Table 1 gives

(a) Shaking Table with model slope



(b) Instrumented rock slope model

Figure 1. A typical set-up for model tests on the shaking table.

Table 1. Specifications of monitoring sensors and shaking table.

Shaking table and sensors	Specification	
Shaking table AKASHI	Frequency	1–50 Hz
	Range	600 Gal
	Stroke	100 mm
Accelerometers TOKYO SOKKI	Range	10,000 Gal
Laser displacement sensors		
KEYENCE LDT	Range	1–100 mm
OMRON LDT	Range	1–300 mm

the specifications of the shaking table and monitoring devices. A stopper was utilized to prevent for breakage model slopes upon failure. Therefore, the maximum sliding displacement was limited to 12–13 mm. The input base wave on the shaking table was horizontal. Experiments were carried out using sinusoidal acceleration waves to simulate earthquakes with a given frequency and a maximum base acceleration up to 670 gals.

3 MATERIAL PROPERTIES

3.1 *Friction angle of failure plane*

The rock block of the experiment model is made of Ryukyu-limestone. In hard rock, the influence of rock deformation is small and the effect of the slip surface becomes dominant. Therefore, the tilting test is conducted for checking frictional properties. Figure 2 shows a view of a tilting test. Figure 3 shows an example of the determination of the dynamic friction angle from the displacement response measured in a tilting test. The peak friction angle ranged between 39.9 and 40.8 degrees while the kinetic friction angle ranged between 22.6 and 26.1 degrees.

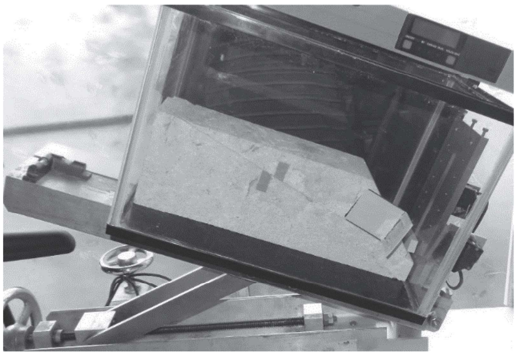


Figure 2. A view of tilting experiments.

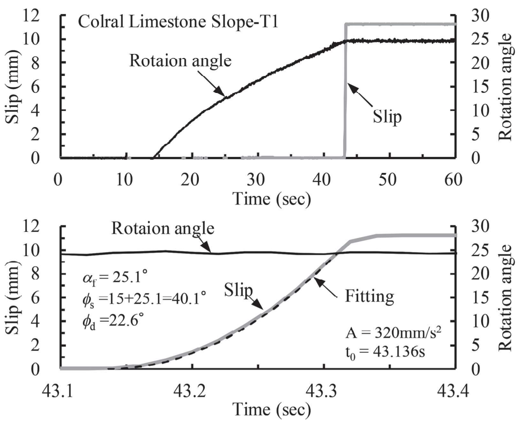


Figure 3. A typical tilting test result and determination of kinetic friction angle.

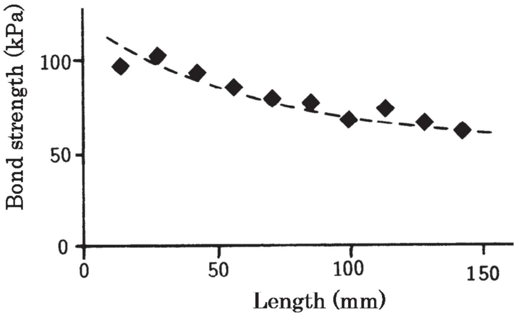


Figure 4. Bond strength of model rockbolts.

3.2 *Bonding capacity of model rockbolts*

The width of rockbolt models was 10 mm and they were made of cello-tapes. Some pull-out tests on the model rockbolts were carried out and results are shown in Figure 4. These model rockbolts may be visualized as fully grouted rockbolts.

4 SHAKING-TABLE TESTS ON MODEL SLOPES

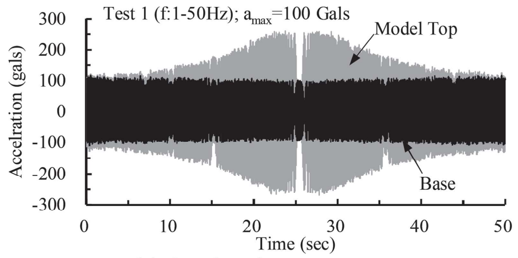
4.1 *Unreinforced layered rock slopes*

A series model tests on rock slopes using layered coral limestone was carried out. Before each failure test, a sweeping test was carried to check the natural frequency characteristics of model rock slopes with a frequency ranging between 1 and 50 Hz at constant acceleration of 100 gals. Figure 5 shows horizontal acceleration records of the shaking table and the top of model slope. The results clearly indicate that model rock slopes has some natural frequency characteristics.

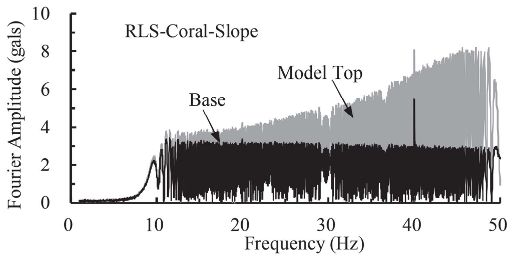
Figure 6 shows the views of layered rock slope models while Figure 7 shows the measured acceleration and relative slip responses. One of interesting observation is that the unstable layered part of the slope moves as a monolithic body until it is restrained by the stopper. Then, the upper unstable layers start to move individually. In other words, there is no essential difference regarding the overall slip behavior of unstable part whether it is a monolithic body or layered. This fact is quite important when the stability assessment methods are developed. The critical acceleration to initiate the slip of the potentially unstable part ranged between 330–350 gals.

4.2 *Experiments on reinforced rock slope models*

A series of experiments were carried out to investigate the number and length of rockbolts on the layered rock slope models. Figure 8 shows views

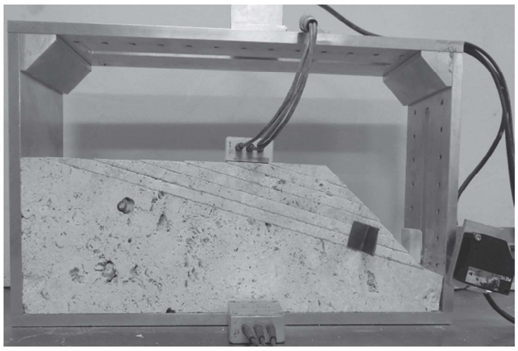


(a) Acceleration responses

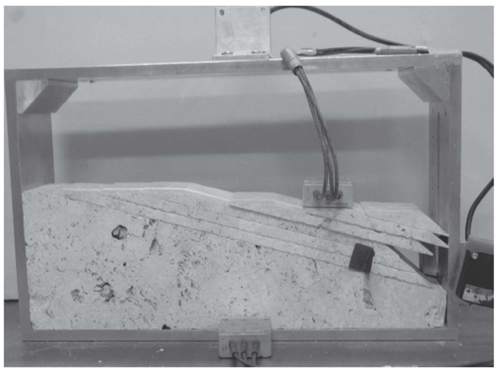


(b) Fourier spectra

Figure 5. Horizontal acceleration records of the model rock slopes and their Fourier spectra.



(a) Before shaking



(b) After shaking

Figure 6. Views of layered rock slope models before and after shaking.

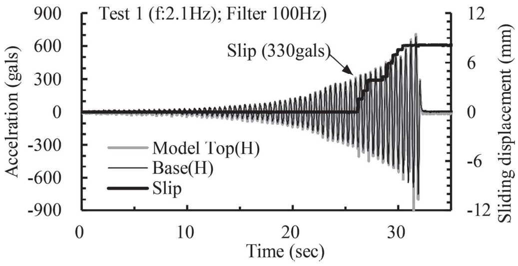


Figure 7. Acceleration and slip response of unreinforced layered rock slope model.

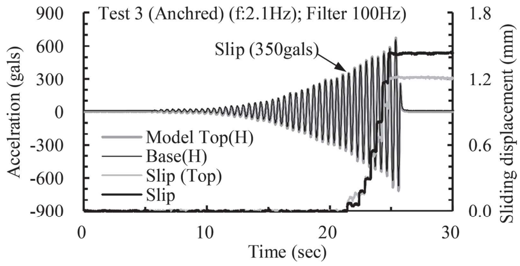
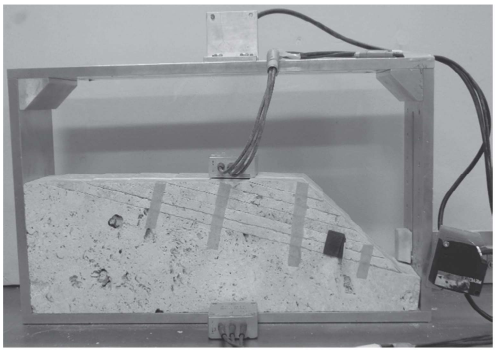
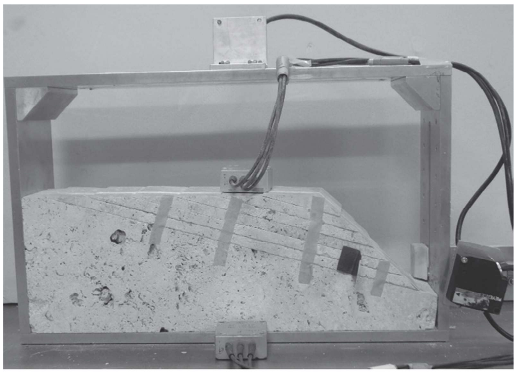


Figure 9. Measured acceleration and slip responses of reinforced layered rock slope model.

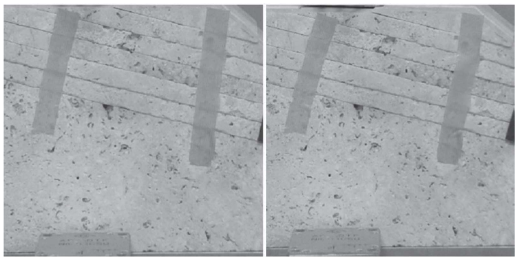


(a) Before shaking



(b) After shaking

Figure 8. Views of reinforced layered rock slope models before and after shaking.



(a) Before shaking (b) After shaking

Figure 10. Views of rockbolts model before and after shaking.

of the reinforced layered rock slope model before and after shaking. Figure 9 shows the measured responses. As the rockbolts are initially not pre-stressed a small amount of slip occurs, this value is almost the same as that for unreinforced case (Figure 10). However, rockbolts restrain the movement of potentially unstable part of the layered model slope after a slip of 1.2–1.6 mm relative slip.

Some tests were carried out to check the effect of length of rockbolts on the layered rock slope models (Figure 11). Figure12 shows the measured acceleration and slip response of the layered rock slope model with rockbolts not crossing the failure plane. In other words, the unstable part of the rock slope model was stitched to create like a monolithic block above the potential failure plane. Although the initiation of slip was slightly higher than that of the unreinforced layered rock slope model, the rockbolts did not act to restrain the movement of the potentially unstable part of the slope. This fact implies that if rockbolts are not anchored into the stable part below the potential failure, the effect of rockbolting or rock anchoring would be none. Therefore, the short rockbolts installed in slopes would not effect any major reinforcement effect on the stability of rock slopes prone to planar sliding except preventing to relative sliding of small blocks above the potential failure surface.

Next, the length of rockbolts was increased and they had anchorage length in the stable part. However, the length was not sufficient to prevent the sliding failure after a given acceleration level. Figure 13 shows the measured acceleration and relative slip responses. The initiation of slip was almost the same as that for unreinforced case, the total collapse of the unstable part was caused at an acceleration level of 450 gals. These examples

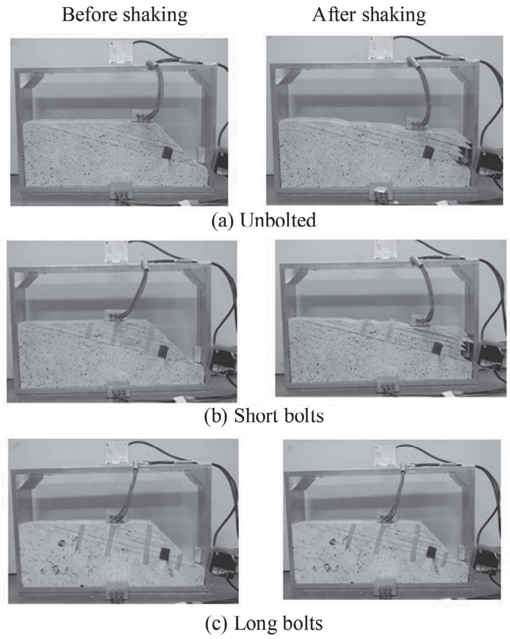


Figure 11. Views of layered rock slope model with fully grouted rockbolt models.

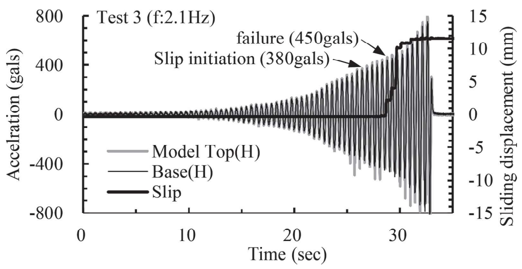


Figure 12. Measured acceleration and slip responses of reinforced layered rock slope model with rockbolts not crossing the failure plane.

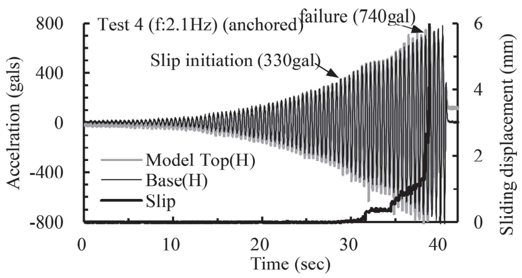


Figure 13. Measured acceleration and slip responses of reinforced layered rock slope model with rockbolts crossing the failure plane.

clearly showed that the rockbolts must have sufficient length anchored in the stable part of the slope and number to prevent the failure of the slope against planar sliding.

5 DYNAMIC LIMITING EQUILIBRIUM METHOD

As the deformation of rock slope occurs mainly due to slippage along the failure surface, a dynamic limiting equilibrium method developed originally by Aydan & Ulusay (2002) and elaborated by Aydan et al. (2008) and Aydan & Kumsar (2010) was used to simulate the slip of the model slope on the failure surface. Figure 14 shows a view of the mechanical model for dry condition with the consideration of the experimental fact, that is, the unstable part moves like a monolithic body irrespective of layered or single body.

One can easily writes the following limiting equilibrium equations for s and n directions, respectively, as follows:

$$W_t \sin\alpha + E\cos\alpha - T\cos(\alpha-\beta) - S = m\frac{d^2 s}{dt^2} \quad (1a)$$

$$W_t \cos\alpha + E\sin\alpha - T\sin(\alpha-\beta) - N = m\frac{d^2 n}{dt^2} \quad (1b)$$

Let us assume that the inertia force for n-direction during sliding is negligible and the resistance of the failure plane is purely frictional as given below

$$\left|\frac{S}{N}\right| = \tan(\phi) \quad (2)$$

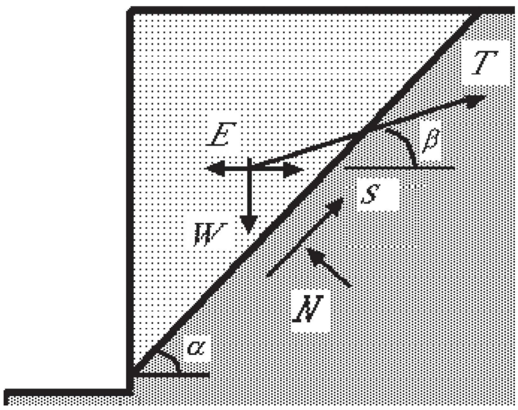


Figure 14. Mechanical model for reinforced rock slope.

One can easily obtain the following equation for the rigid body motion of the sliding rockmass body

$$m\frac{d^2s}{dt^2} = A_W + A_E - A_T \tag{3}$$

where

$$A_W = W_t(\sin\alpha - \cos\alpha\tan\phi)$$
$$A_E = E(\cos\alpha + \sin\alpha\tan\phi)$$
$$A_T = T(\cos(\alpha-\beta) + \sin(\alpha-\beta)\tan\phi)$$

As the earthquake force E will be proportional to the mass of the sliding body, it can be related to ground shaking in the following form:

$$E = \frac{a_g(t)}{g}W_t \tag{4}$$

where α_g is base acceleration, g is gravitational acceleration.

The axial force in a rockbolts may be given in the following form (Aydan 2018).

$$T = B\delta^b \tag{5}$$

where b and B are empirical constants. It is experimentally well-known that the rockbolts crossing a discontinuity plane is bended during shearing and there is an effective length of rockbolts mobilized during the shearing process. Thus, the extension of rockbolt would be given by

$$\delta = \ell - \ell_o = \sqrt{(\ell_o + \delta_h)^2 + \delta_v^2} - \ell_o \tag{6}$$

where ℓ_o, δ_h and δ_v are the effective length of rockbolt mobilized at the failure plane and horizontal and vertical movement of the sliding unstable body. The force in the rockbolt can then be obtained by inserting the extension value from Eq. (6) into Eq. (5).

The mathematical model described in this section can be used for both unreinforced and reinforced rock slopes. For unreinforced case, the resistance provided by rockbolts would be neglected.

6 COMPARISONS

A comparison of estimations from the dynamic limiting equilibrium method is shown in Figure 15. Three different values are used for the kinetic (residual) friction angle. In these particular simulations, if the slip stops, the peak friction angle was used for the initiation of slip in the next cycle. Although it is not reported herein, the slip becomes much larger if the friction angle is assumed to be equal to residual value once the slip is initiated. The values used in computations are also shown in Figure 15. The initiation of the slip occurred slightly at a higher friction angle than that determined from tilting test. Figure 16 compares the slip responses for three different values of residual friction angle. When the residual friction angle is equal to the peak friction angle, which corresponds to perfectly plastic behaviour, the amount of slip is quite smaller than those for lower residual friction angle. When the residual friction angle is 0.625 times the peak friction angle, it corresponds to the kinetic friction angle determined from tilting tests. For this particular situation, the slip is largest. When the residual friction angle is 0.725 times the peak friction angle, the slip at the first stage is equal to that measured in the experiment as seen in Figure 16. It is very likely that if the peak friction angle is reduced as a function of the slip cycles, it is quite possible to get better estimations of the measured

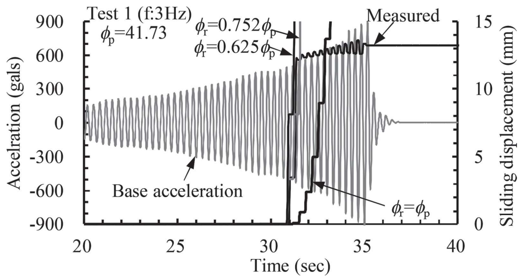


Figure 15. Comparison of measured slip response with the estimated responses for different values of residual friction angle.

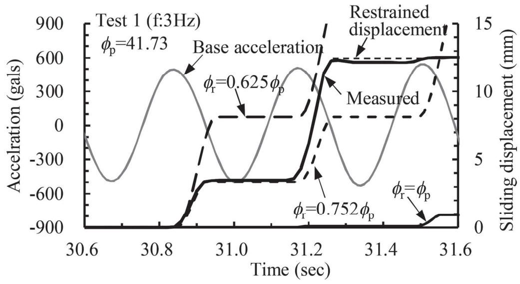


Figure 16. Expanded comparison of measured slip response with the estimated responses for different values of residual friction angle, shown in Figure 14.

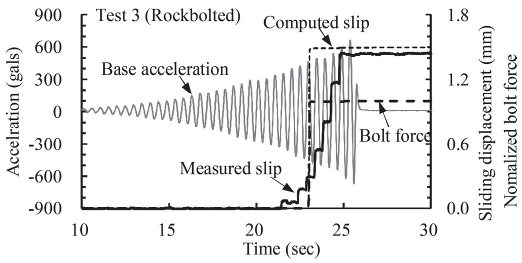


Figure 17. Comparison of computed responses with measured responses.

responses. It should be noted that the slip of the potentially unstable block is restrained to 12.3 mm and the displacements exceeding this value is out of considerations.

The theoretical approach is applied to model tests shown in Figure 9 by selecting that the friction angle is 39°. The computed results are shown in Figure 17. As noted from the figure, the computed results are quite similar to experimental results both quantitatively and qualitatively. However, the computations indicate that the yielding should start a bit later than the measured results. The discrepancy may be resulting from the complexity of actual frictional behavior of sliding surface. Nevertheless, the theoretical model is capable to model the dynamic response of the support system.

7 CONCLUSIONS

In this study, shaking table tests of rock slope with sliding block on inclined failure surface are conducted and the dynamic response of sliding block was measured. To simulate the block interaction such as sliding or separation, the numerical simulations are conducted by the dynamic limit equilibrium method and the applicability of analytical method is verified. The findings obtained from this study can be summarized as follows.

1. The behavior of slip indicates is close to the experimental result if dynamic friction angle is considered in the dynamic limit equilibrium method and the finite element method.
2. The slip start time can be evaluated by the finite element method in which considering of "slip" and "separation" are considered.
3. The slip displacement can be evaluated by the dynamic limit equilibrium method and the behavior of upper-block agrees with the behavior of rigid model.

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