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Failure mechanism and effective reinforcement of granular soil slope

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ABSTRACT: The model tests of the slope called "tilting box test" are carried out on aluminium rod mass, which is used as a two-dimensional model of granular materials, and sand in dry and wet states. Based on the test results, the failure mechanism and the effective reinforcement of the granular soil slope are considered. It becomes clear from the test results that the rolling of soil particles on the surface of the slope is a "trigger" of the whole failure of the granular soil slope, the sliding like a rigid body along a slip line is not observed, and therefore the method of reinforcement to stop the motion of particles on the surface of the slope is unexpectedly effective.

1. INTRODUCTION

In order to consider the failure mechanism and the effective reinforcement of the granular soil slope, the model tests of inclining a slope called "tilting box test" are carried out on aluminium rod mass with various kinds of reinforcement, which is used as a two-dimensional model of granular materials, and the test results are observed by the slow motion pictures of the video tape taken during the tests. It is found from the observation of the test results that the rolling of soil particles on the surface of the slope is a "trigger" of the whole failure of the granular soil slope, and therefore the method of reinforcement to stop the motion of particles on the surface of the slope by a sticky tape is unexpectedly effective.

Another kind of "tilting box test" is performed on a dry sand (Toyoura sand; D_{50}=0.2mm, U_c=1.3) and the same sand with the wet surface (2~3mm in depth) by a spray-gun, which has a little cohesion between sand particles due to the surface tension of water. The test is also performed on the sand with the wet surface reinforced by a thin parallel-crossed plastic frame. The application of these test results to the real granular soil slope is taken into consideration (Matsuoka and Sugiyama, 1994).

2. TEST PROCEDURE

A stack of cylindrical aluminium rods 50mm in length, (a) 1.6mm and 3mm in diameters and (b) 5mm and 9mm in diameters is used as a sample of the two-dimensional granular soil slope. All the mixing weight ratio of two diameters of these samples is 3:2. Fig.1 shows the model test apparatus of the slope for the two-dimensional rod mass, which is called "tilting box" (Matsuoka et al., 1991). The length of the slope is about 40cm. The model of the granular soil slope ("tilting box") is gradually inclined by an electric motor through a wire rope and the slope failure is induced. The two-dimensional granular soil slope is made by piling the rods (50mm

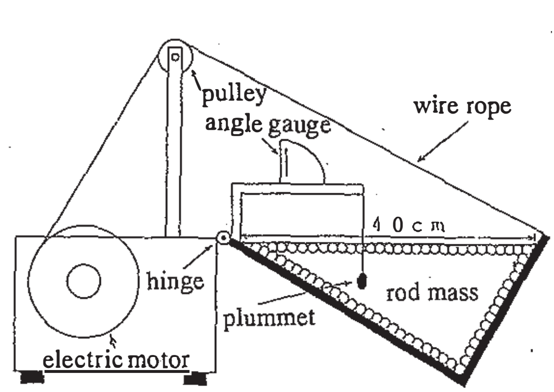


Fig. 1 Model test apparatus of slope called "tilting box"

Table 1 Interparticle friction angle, internal friction angle and slope angle at failure (without reinforcement) of aluminium rod mass

Material	Aluminium rods	
Particle diameters and mixing weight ratio	d1.6:d3=3:2	d5:d9=3:2
Interparticle friction angle : ϕ_μ	19°	19°
Internal friction angle : ϕ	25°	25°
Slope angle at failure (without reinforcement)	30° (2)	29° (4)

(The number in parenthesis denotes the number of tests)

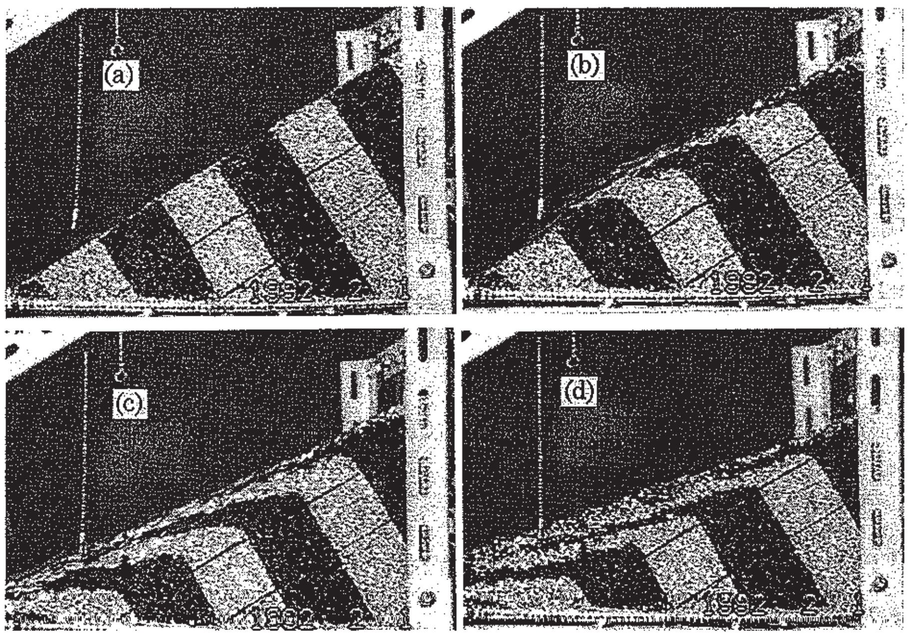


Fig. 2 Failure order of slope of dry aluminium rod mass with black marked lines (Failure order; (a)→(b)→(c)→(d))

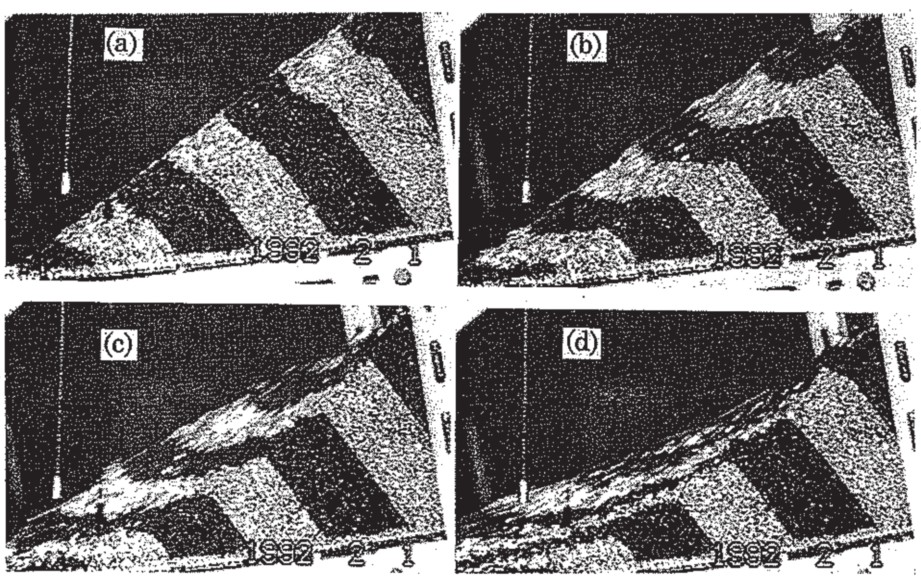


Fig. 3 Failure order of slope of wet aluminium rod mass with black marked lines (Failure order; (a)→(b)→(c)→(d))

in length), which are self-standing, so it is friction-free because it does not need the supporting transparent plates on both the forward and backward sides of the slope of rod mass. The following methods of reinforcement for slope stability are tried; putting thin long flexible weights on the surface of the slope, inserting frictional plates into the slope and fastening sticky tapes on both the forward and backward sides of the surface of the slope (see Fig. 8). The slope angle at the time when the slope starts to fail is read as the slope angle at failure. The deformation of the slope is little before failure, and the failure of the slope occurs in a moment. The pictures of the slope failure are taken by a video camera at a speed of 1/30 sec.. The slow motion pictures of the video tape are observed in detail by a television and photographs through a video printer.

3. FAILURE MECHANISM OF GRANULAR SOIL SLOPE

Table 1 shows the interparticle friction angle ϕ_μ, the internal friction angle ϕ and the average value of the slope angles at failure of the aluminium rod mass (the number in the parenthesis denotes the number of tests). The interparticle friction angle ϕ_μ is determined from the slope angle at which a rod starts to slide on the same rods put at right angles. The internal friction angle ϕ is determined by "biaxial tests" on the same rod mass.

Fig.2 (a)-(d) and Fig.3 (a)-(d) show the slow motion pictures during the slope failure of aluminium rod mass (d1.6:d3=3:2) in dry and wet states respectively, taken by a video camera. The wet aluminium rod mass (water content w≈2.5%) is used to check the effect of interparticle force due to the surface tension of water. It is clearly seen from Fig. 2 and Fig.3 that the particles start to roll and slide firstly from the surface, gradually develop to slide to the inside of the slope, and finally a slip line is formed.

If the slope slides like a rigid body along a circular slip line as generally considered, the slope angle at failure is not expected to change even if the inside of the slip line (the part bounded by the slip line and the slope surface) is fastened by sticky tapes on the forward and backward sides of the aluminium rod mass. Therefore, the slip line of the slope is estimated in the case without reinforcement, and such a model test as shown in Fig. 4 is performed under the condition of fastening the both sides of the inside of the slip line by sticky tapes. The slope angle at failure in this case is 38° and is very different

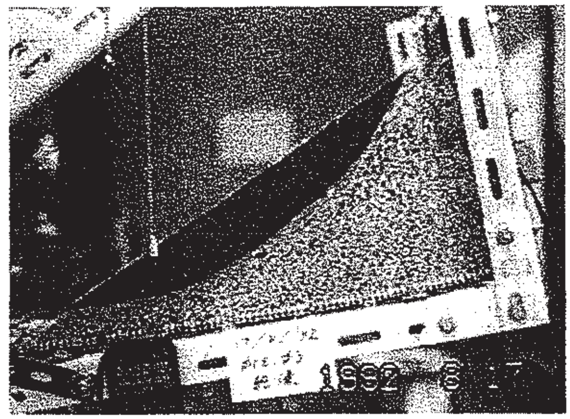


Fig. 4 Failure under condition of fastening the inside of slip line by sticky tapes

Fig. 5 Typical failure pattern along circular slip line

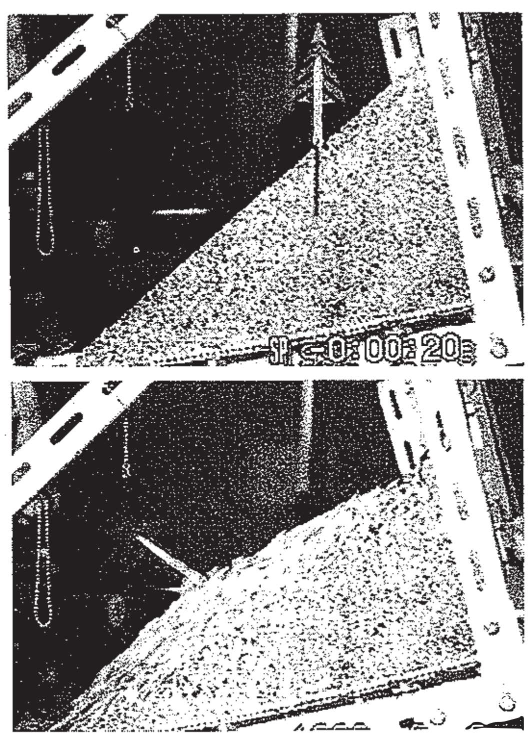


Fig. 6 A falling "tree" on slope of aluminium rod mass

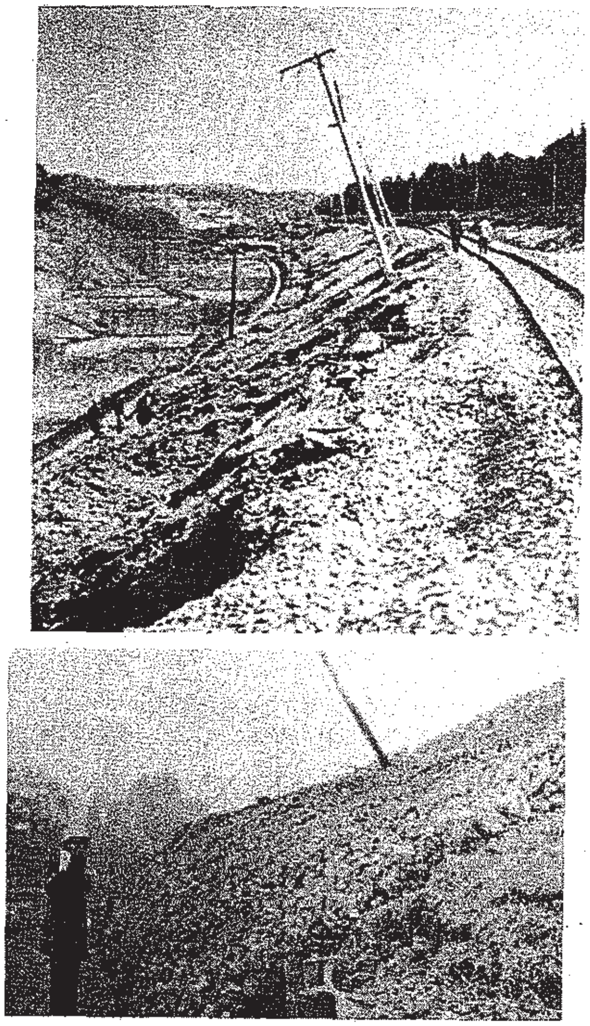
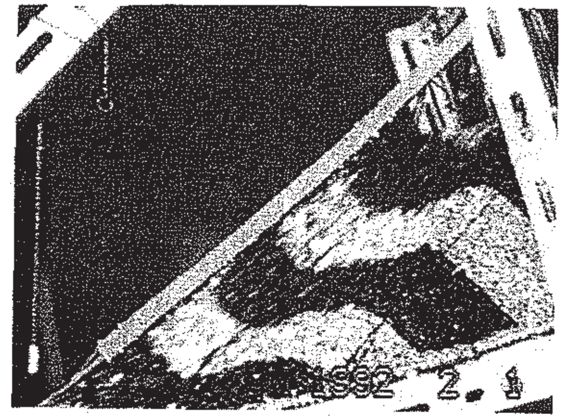
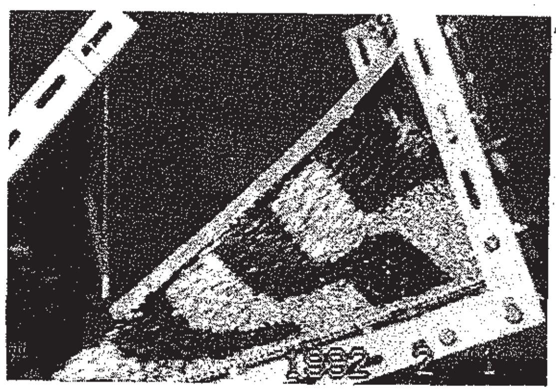


Fig. 7 Inclined electric poles on slope in the field



(a)



(b)

Fig. 8 Failure pattern of slope of aluminium rod mass reinforced by sticky tape (1cm in width) in (a) dry and (b) wet states

from 30° in the case without reinforcement. This test result also supports the failure mechanism of the slope proposed here, that is, "rolling and sliding from the slope surface first and forming something like a slip line finally".

This failure mechanism is quite different from the well-known failure pattern along a circular slip line as shown in Fig. 5. Fig. 6 shows the direction of the falling "tree" standing on the slope of aluminium rod mass. The direction of the falling "tree" is upward in Fig. 5 and downward in Fig. 6. Fig. 7 (a) and (b) show inclined electric poles on the slope in the field, whose falling direction is also downward (Yamada et al., 1968). These results in the field support the failure mechanism of the slope proposed here.

4. REINFORCEMENT BASED ON FAILURE MECHANISM OF GRANULAR SOIL SLOPE

Although some methods of reinforcement for slope stability have been tried as mentioned before, the most effective and interesting method is to stop the "trigger", that is, the rolling of particles on the surface of the slope. To do this, thin sticky tapes (1cm in width) are fastened on both the sides of the surface of the slope (forward and backward edges of rods) as shown in Fig. 8 (a) and (b) in dry and wet states respectively. The length of the sticky tapes is 32.5cm at the upper part of the full slope length (=40cm). The sticky tapes are fastened at the upper edge of the slope to the frame of the "tilting box".

Table 2 shows the slope angles at failure of the aluminum rod mass without reinforcement and with reinforcement mentioned above. It is interesting to know that the slope angles at failure increase greatly only by restraining the movement of particles near the surface of the slope. As seen in Fig. 8, the whole failure of the slope is resisted by the shear strength in the inside of the slope (cf. Figs. 2 and 3).

The dry Toyoura sand (10cm in depth) is set in another "tilting box" (36cm in width, 63cm in length and 30cm in depth) as shown in Fig. 9. The half part

Table 2 Slope angles at failure of aluminium rod mass without reinforcement and with reinforcement by thin sticky tapes in dry and wet states

Particle diameters and mixing weight ratio	d1.6:d3=3:2 (dry)	d5:d9=3:2 (dry)	d1.6:d3=3:2 (wet)
Without reinforcement	30° (2)	29° (4)	42° (6)
Reinforcement by thin sticky tapes (1cm in width, ℓ=32.5cm)	43° (3)	46° (2)	51° (3)

(The number in parenthesis denotes the number of tests)

Table 3 Slope angles at failure of Toyoura sand without reinforcement and with reinforcement (I and II)

Without reinforcement	33° (5)
Reinforcement I (giving wetness on sand surface — 2~3mm in depth)	43° (2)
Reinforcement II (inserting parallel - crossed frame and giving wetness on sand surface — 2~3mm in depth)	55° (2)

(The number in parenthesis denotes the number of tests)

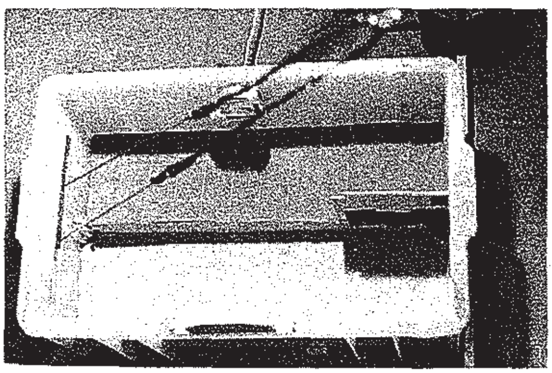


Fig. 9 Another "tilting box test" on Toyoura sand with and without reinforcement

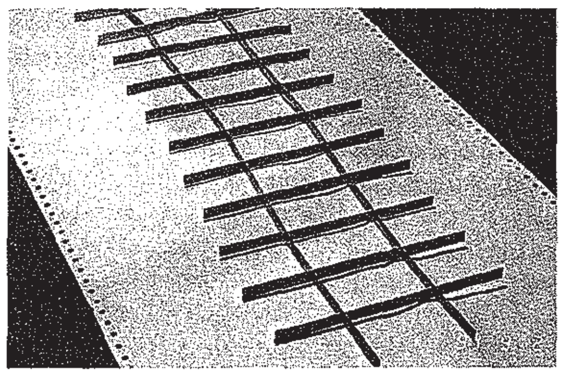


Fig. 10 Thin parallel-crossed plastic frame for reinforcement (1cm in height)

of the sand (18cm in width) is prepared without reinforcement and the another half part (18cm in width) is prepared with reinforcements as follows; reinforcement I is to give wetness on the surface of the sand (2~3mm in depth) by a spray-gun and reinforcement II is to insert a thin parallel-crossed plastic frame (see Fig. 10) in the sand (1cm in depth) which is fastened at the upper edge of the slope, and give wetness on the surface of the sand (2~3mm in depth). It is seen from Table 3 that the reinforcements for the surface of the slope have an unexpectedly big effect on the slope stability. The method of setting a parallel-crossed concrete frame on the surface of the slope is seen in the field, but it is not expected to increase the slope stability so much. It is a completely new idea to fasten (or pull) a frame at the upper part of the slope in order to increase the slope stability.

5. CONCLUSIONS

The main results are summarized as follows;

1) It is seen from the results of "tilting box test" on aluminium rod mass that the particles on the surface of the slope start to roll when the normal direction of

the interparticle contact coincides with the direction of the gravity, and this is a "trigger" of the whole failure of the granular soil slope.

2) It is observed from the slow motion pictures of the video tape that the particles start to roll and slide firstly from the surface of the slope, gradually develop to slide to the inside of the slope and finally a slip line is formed. The sliding like a rigid body along a slip line is not observed in the case of the granular soil slope.

3) Based on the failure mechanism of the granular soil slope mentioned above, the method of reinforcement to stop the movement and rolling of particles along the surface of the slope is proposed.

4) In order to stop the movement and rolling of particles along the surface of the slope, the following methods are adopted in the tests; (a) thin sticky tapes (1cm in width) are fastened on both the forward and backward edges of aluminium rods, and (b) a thin parallel-crossed frame is inserted in the sand (1cm in depth) and wetness is given on the surface of the sand (2-3mm in depth) by a spray gun. The wetness produces a little cohesion between sand particles due to the surface tension of water. It is seen from the test results that such reinforcements for the surface of the slope as mentioned above have an unexpectedly big effect on the slope stability.

5)The method of setting parallel — crossed concrete frame on the surface of the slope is seen in the field, but it is not expected to increase the slope stability so much. It is a completely new idea to fasten (or pull) a frame at the upper part of the slope in order to increase the slope stability.

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