New Horizons in Earth Reinforcement – Otani, Miyata & Mukunoki (eds)

Shaking table tests on the mechanism to stabilize slopes by steel nails during earthquakes

S. Yasuda, C. Higuchi & C. Ishii
Tokyo Denki University, Saitama, Japan

N. Iwasa
Nippon Steel & Sumikin Metal Products, Tokyo, Japan

ABSTRACT: Several shaking table tests were carried out to study the mechanism to stabilize slopes by steel nails. Weathered granite soil was filled in a soil container. Then the soil was strengthened by iron rods, plates and wire ropes. Five types of model slopes were selected: i) without iron rods, ii) with non-anchored iron rods, iii) with anchored iron rods, iv) with anchored iron rods, and connected by wires, and v) with iron rods, but the plates are small. Test results showed that this method is effective to prevent slope failure. And it was clarified that combination of iron rods, plates and wire ropes is important.

1 INTRODUCTION

One slope in Kashiwazaki City was protected by Non-frame method, which is a steel nailing method, in spring of 2004 in Japan. Heavy rain and Typhoon hit the slope in July and October. No deformation occurred due to two triggers. Moreover, the 2004 Niigataken-chuetsu earthquake hit this area on October 23. Liquefaction-induced damage to houses occurred at several sites in Kashiwazaki City. However, no deformation was induced at the treated slope. In 2005, Fukuokaken-seiho-oki earthquake occurred and caused slope failure at several sites. However, one slope protected by the method at Sawara-ku in Fukuoka City, shown in Photo 1, was also stable. These examples imply the effectiveness of this method during earthquakes. Seismic intensities at the treated slopes during two earthquakes were about 5 in JMA scale.

Non-frame method is one of the nailing methods to stabilize natural slopes against heavy rains and earthquakes. In this method bore holes are drilled with triangle alignment as shown in Figure 1. Iron rods are inserted in the bore holes. Tips of the iron rods are inserted in stable rock or soil for 1 m. The bored holes are grout-filled with mortar. Then, place plates and caps at the top of the rods. The plates are connected by wire ropes. Thus unstable layers of a slope can be stabilized by the combination of the iron rods, plates and wire ropes. This method can be applied without cutting existing trees. Therefore, stabilizing effect by the roots of existing trees is not diminished. Moreover, treated slopes are beautiful because the slopes are covered with natural grasses and trees. As drilling machines are small and light, the method can be applied to steep slopes.

Photo 1. Treated slope by Non-frame method in Fukuoka.

The method must prevent failure of slopes due to the following three effects:

(1) prevent the slide of soil mass by bending resistance of iron rods,
(2) prevent the deformation of slope surface by the pressure between plates and slope surface
(3) prevent the deformation of slope surface by the pressure between wire ropes and slope surface

However, these effects during earthquakes are not clear. Then the authors conducted shaking table tests to demonstrate the mechanism of stabilization and effect of each factor.

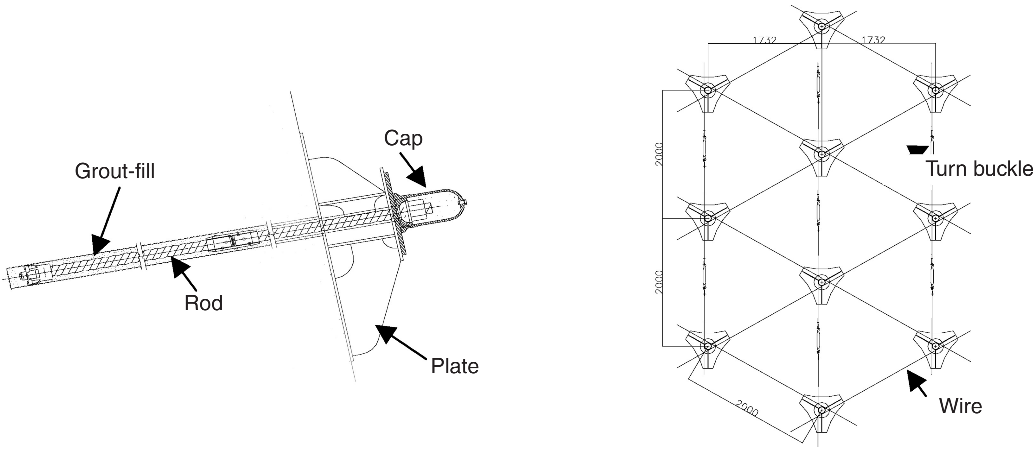

Figure 1. Non-frame method.

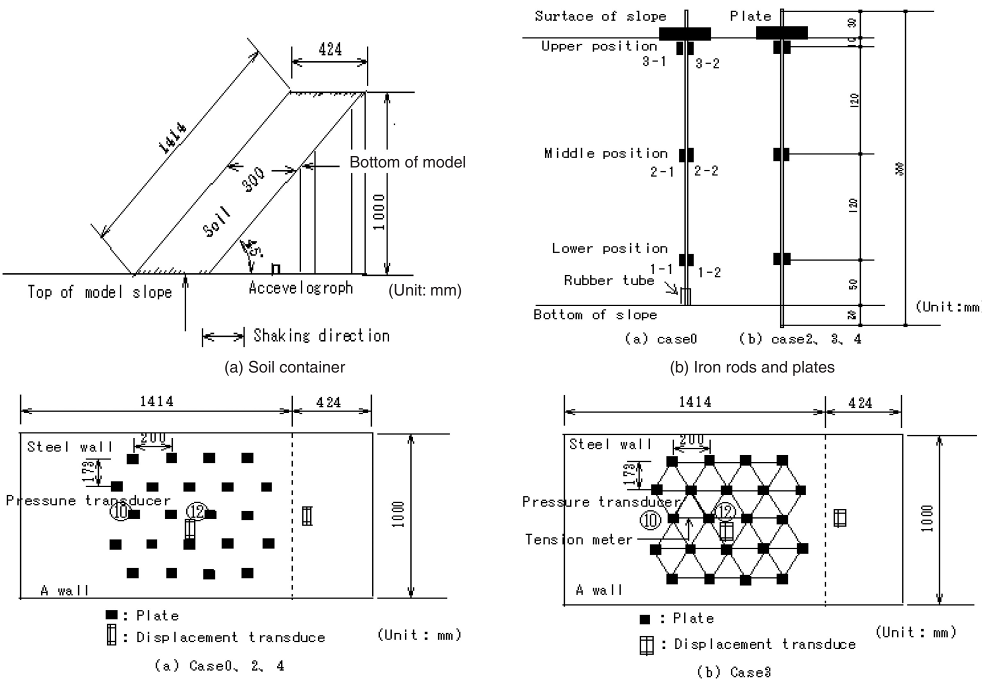

Figure 2. Soil container, iron rods and plates.

2 METHOD OF SHAKING TABLE TESTS

Several 1G shaking table tests were carried out to study the mechanism of the Non-frame method. In these tests, a soil container with a length of about 1,400 mm and a depth of about 400 mm was used as shown in Figure 2. Model iron rods were stood on the base plate of the soil container. Then weather granite soil was filled with a thickness of 100 mm. Fines content of the weathered granite is 14.2%. The soil was compacted in two densities, (1) loose: $\rho_t = 1.5\ \mathrm{g/cm^3}$, Dc = 70.8%, and (2) dense: $\rho_t = 1.6\ \mathrm{g/cm^3}$, Dc = 75.5%. After the compaction of the first layer, the following other layers were filled and compacted in the same way. Plates and wires were connected at the top of the iron rods. Then the soil container was tilted to make a slope.

Table 1 shows test conditions. Five types of model slopes were selected for loose soil: i) without iron rods,

Table 1. Test conditions and test results.

Test No.	Anchore of nails to bottom plate	ρ_t (g/cm^3) W(%) Dc(%)	Plate Shape	Width (mm)	Thickness (mm)	Tension of wire	Critical Acceleraiton (gal)
Case 0	Non-anchored	$\rho_t = 1.5$ W = 11.5	Square	50	5	–	650
Case 1	–	Dc = 70.8		–	–	–	295
Case 2	Anchored		Square	50	5	–	911
Case 3	Anchored		Square	50	5	3N	947
Case 4	Anchored		Square	30	5	–	770
Case D1	–	$\rho_t = 1.6$ W = 5.0	–	–	–	–	410
Case D2	Anchored	Dc = 75.5	Square	50	5	–	899

W: Water content, DC: Degree of compaction.

(a) Case 1 (b) Case 0 (c) Case 3

Photo 2. Failed slopes at critical acceleration.

ii) with non-anchored iron rods,, iii) with anchored iron rods,, iv) with anchored iron rods, and connected by wires, and v) with iron rods, but the plates are small. And, two types of model slopes were selected for dense soil.

Fifty cycles of sine waves at 5 cycles/s were applied to these model slopes. Acceleration of the shaking increased from 50 Gals up to the acceleration to cause slope failure, with an increment of 50 Gals. Occurrence of the slope failure was judged when some zone failed as shown in Photo 2. The input acceleration to cause the slope failure is called as the critical acceleration hereafter. During the shaking, accelerations on the ground surface, displacements of the ground surface, stresses of iron rod, stresses of wires and pressures of plates were measured, as shown in Figure 2.

3 TEST RESULTS

3.1 *Critical acceleration to cause failure*

Critical accelerations are shown in Table 1. In Case 1, settlement of top of the slope increased with input acceleration. Then entire slope failure occurred when input acceleration reached to 295 Gals, as show in Photo 2(a). After the test, the ground was excavated carefully. A clear slip surface was observed at the depth of about 10 cm. In Case 0, settlement of top of slope increased with input acceleration also. When the input acceleration reached to 650 Gals, non-treated zone failed as shown in Photo 2(b). As the critical acceleration was higher than that in Case 0, it can be said that the inserted iron rods resisted against sliding, even the iron rods were not anchored to base steel plate.

In Cases 2 and 3, no obvious settlement or deformation occurred in treated zone even input acceleration exceeded 900 Gals. Partial sliding occurred in non-treated zone when input acceleration exceeded 900 Gals, as shown in Photos 2(c). Anchored iron rods were very effective to resist against sliding. By comparing Case 2 and Case 3, deformation of the slid soil in Case 3 was smaller than that in Case 2. Therefore, it seemed that wire ropes prevented the deformation of slope.

In Case 4, slide occurred at 770 Gals. The critical acceleration to cause failure was smaller than that in Case 2. Size of plates must be important.

Critical acceleration in Case D1 was high as 410 Gals. It was about 1.5 times compared with the critical acceleration in Case 1. Soil density fairly affected the critical acceleration.

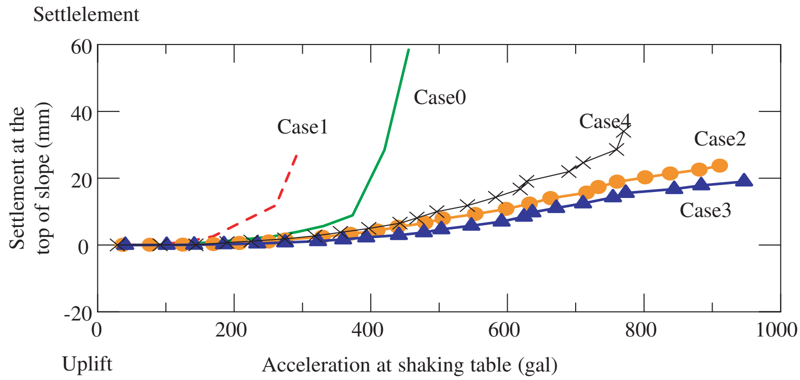

Figure 3. Relationships between input acceleration and settlement at the top of slope (loose soil).

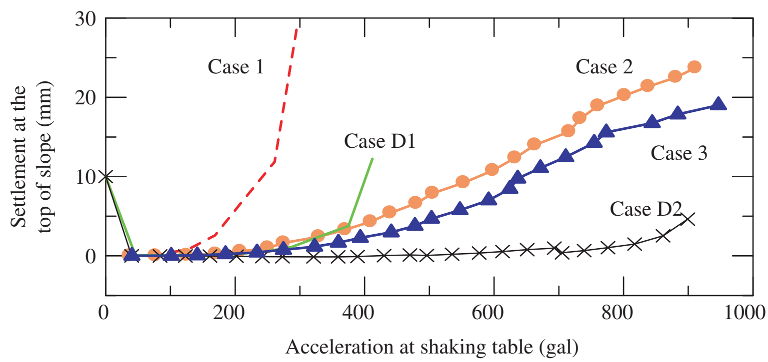

Figure 4. Effect of soil density on the settlement at the top of slope.

3.2 *Comparison of settlement of the top of slope*

Figure 3 shows relationships between input acceleration and settlement of top of slope. Settlement increased with input acceleration in all case. However, amount of settlement was different in each case. The settlement in Case 3 was smallest. And the settlement increased in the order of Case 2, Case 4, Case 0 and Case 1. The order was same as the order of critical acceleration to cause failure, as mentioned before.

At 600 Gals, the settlement in Case 2 was 3 to 6 mm less than that in Case 4. This difference must be attributed to the difference of size of plates. The settlement in Case 3 was about 6 mm less than that in Case 2. This implies the importance of wire ropes.

Figure 4 shows effects of soil densities on the settlement. Settlement increased gradually with increase of acceleration in loose soils. On the contrary, in dense soils, settlements occurred suddenly if acceleration exceeded the critical accelerations.

3.3 *Bending strain and axial strain of iron rods*

Figure 5 shows relationships between input acceleration and bending strain of iron rods in Case 0 and Case 2. In case 2, bending strain of the middle iron rods increased with input acceleration. At lower iron rods, bending strain decreased with input acceleration. In Case 0, on the contrary, bending strain did not increase up to the acceleration of 400 Gals. This means that iron rods were pulled out from base plate when input acceleration reached 400 Gals.

Figure 6 shows effects of soil density on the bending strain. In Case D2, bending strain did not increase with acceleration. Therefore, it seems that bending resistance can not be displayed in dense soils.

Relationships between input acceleration and axial strain are shown in Figure 7 for Case 0 and Case 2. In Case 2, axial strain decreased with input acceleration, because soil was compacted due to shaking. In contrast, axial strain in Case 0 increased with input acceleration. Iron rods must be stretched due to sliding of soil.

Figure 8 compares axial strains in Cases 2 and D2. Axial strain in Case 2 decreased with acceleration, mentioned above. On the contrary, axial strain in Case D2 increased with acceleration.

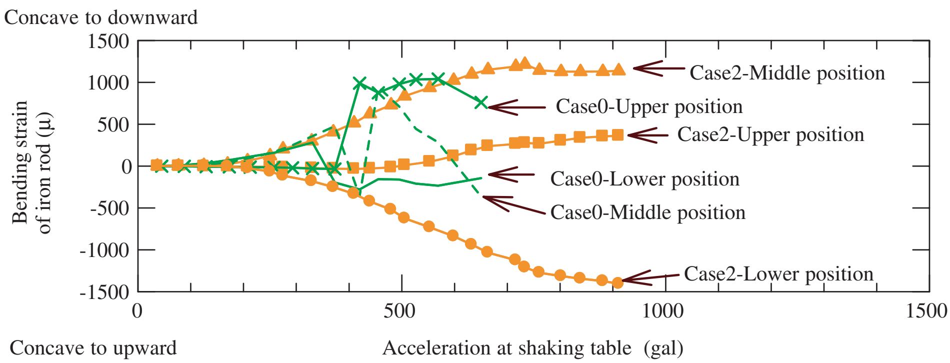

Figure 5. Relationships between input acceleration and bending moment of iron rod (Case 0, Case 2).

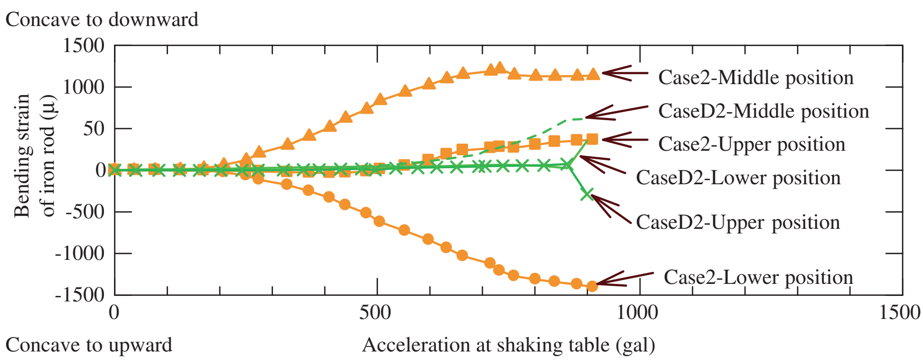

Figure 6. Effect of soil density on the bending strain of iron rod.

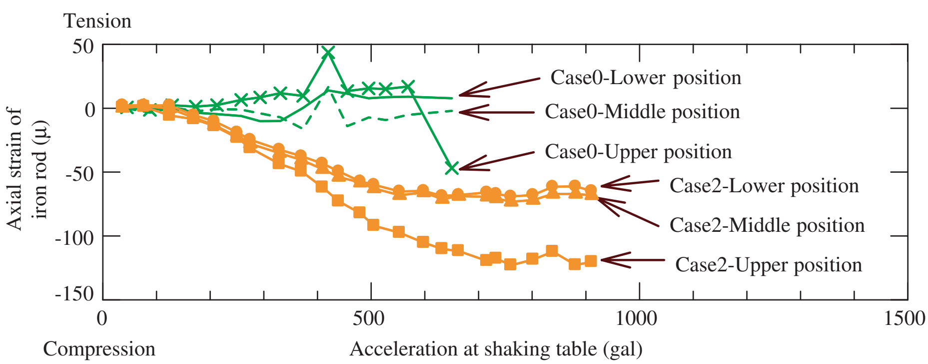

Figure 7. Relationships between input acceleration and axial strain of iron rod (Case 0, Case 2).

3.4 *Settlement of slope surface*

Figure 9 shows relationships between input acceleration and settlement measured at the middle of slope surface. In Case 2, settlement at the center of the slope surface increased with input acceleration. In contrast, slope surface heaved in Case 1 and Case 4. The heaving occurred when input acceleration reached to about 400 Gals and 600 Gals for Case 1 and Case 4, respectively. In Case 3, ground surface did neither settle nor heave. Wire ropes must prevent the settlement or heaving.

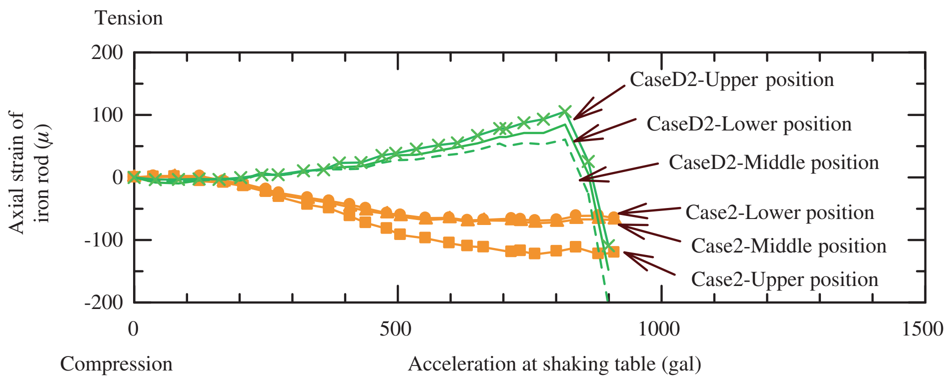

Figure 8. Effect of soil density on the axial strain of iron rod.

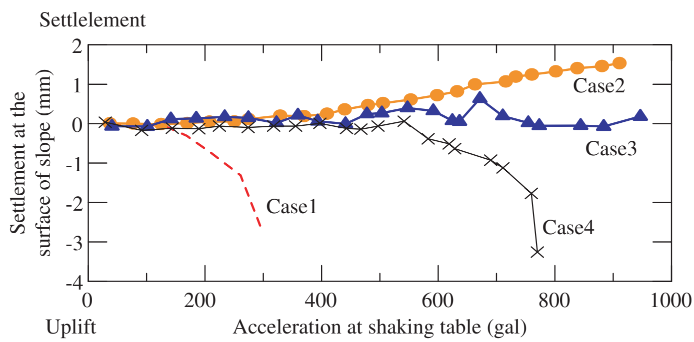

Figure 9. Relationships between input acceleration and settlement at the surface of slope.

4 CONCLUSIONS

Several 1G shaking tests were conducted to study the mechanism of the Non-frame method during earthquakes. The following conclusions were derived through the tests:

(1) Non-frame method is effective to prevent slope failure during earthquake.
(2) Iron rods must be fixed to stable bottom layer.
(3) Large plates are effective than small plates.
(4) Wire ropes can increase the resistance against failure.
(5) Bending and axial stresses acted on iron rods are affected by soil density.

ACKNOWLEDGEMENT

The authors would like to express their thanks to Miss A. Yamada, former students at Tokyo Denki University, for her cooperation in carrying shaking table tests.

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