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Seismic stability of several types of retaining walls on sand slope

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ABSTRACT: Model shaking tests using an irregular base shaking were performed to investigate the failure mechanism and seismic stability of five types of soil retaining walls (RWs) constructed on sand slope. Conventional leaning-type and cantilever RWs exhibited brittle failure at a relatively low base acceleration. A reinforced-soil RW showed ductile and highly seismic-resistant behavior. Leaning-type and reinforced-soil RWs, both with nails in the backfill and slope, exhibited the highest seismic stability, showing small displacements even when subjected to a base acceleration higher than 1g. Nailing could be one of the best ways to stabilize existing leaning-type RWs on slope, while reinforced-soil RWs with nails could be most cost-effective as newly constructed RWs on slope.

1 INTRODUCTION

In many previous major earthquakes, a number of earth structures, including retaining walls, were seriously damaged. During the 1995 Hyogoken-Nanbu earthquake in Japan, conventional soil retaining walls (RWs), i.e. gravity type, leaning type and cantilever RWs, constructed on level ground were seriously damaged, while reinforced-soil RWs with full-height rigid facing performed very well (e.g., Tatsuoka et al., 1997). This fact indicates that on level ground, reinforced-soil RWs have higher seismic stabilities than conventional ones. On the other hand, the 1999 Chi-Chi earthquake in Taiwan caused serious damage to a number of RWs in mountain areas. In particular, a great number of gravity-type and leaning-type RWs constructed on slope failed seriously.

In order to investigate into the seismic stability of RWs, several series of model tests have been conducted so far. In most of them, the seismic stability of RWs constructed on level ground was evaluated. (e.g., Koseki et al., 1998,2001, Watanabe et al., 2001). However, in practical cases, RWs are often constructed on slope, especially in mountain areas. When the subsoil is sloped, the RWs would undergo bearing capacity failure more easily than those on the level ground.

In this study, therefore, in order to investigate the failure mechanism and seismic stability of RWs constructed on slope, five types of model RWs were constructed on a shaking table and subjected to irregular base shaking. Based on the test results, effects of soil nailing in improving the seismic stability of existing conventional RWs and newly-constructed reinforced-soil RWs on slope are demonstrated.

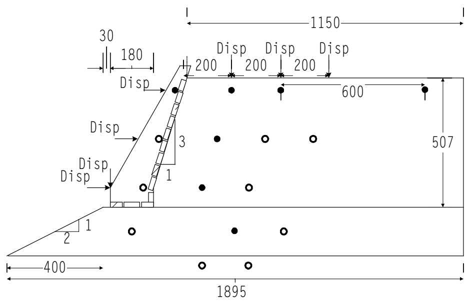
2 MODEL RETAINING WALLS AND TEST PROCEDURES

The cross-sections of five different model RWs and the arrangement of transducers are shown in Fig. 1. The models are a) leaning-type RW (a sort of gravity-type); b) cantilever RW; c) geogrid-reinforced soil RW having a full-height rigid (FHR) facing; d) leaning type RW with two layers of large-diameter (LD) nails; and e) geogrid-reinforced soil RW having a FHR facing with one layer of LD nails. The height of the model RWs ranged from 50 cm to 53 cm.

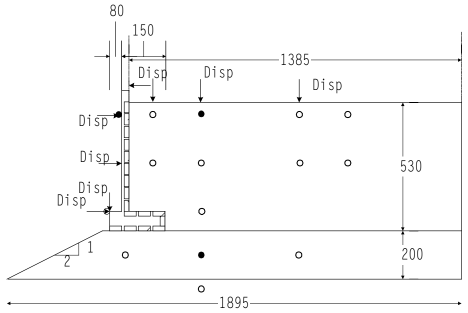
In a sand box with a width of 60 cm, they were constructed on sand slope having a thickness of 20 cm between the crest and the bottom of the sand box and a slope of 2:1(H:V) with a setback of 3 cm between the toe of RW and the slope crest. To measure the response of each RW during horizontal shaking of the sand box, a number of displacement transducers and accelerometers were installed. The transducers were arranged in such a way that the response among different types of walls could be easily compared. Shear load in the vertical direction and normal lateral load acting on the back and bottom faces of wall were measured with a number of small two-component load cells that were set on the back and bottom of wall. For the RW models with LD nails, mortared columns were used as model reinforcement nails. The details of the LD nail are shown in Fig. 2. Four columns were placed at a horizontal center-to-center spacing of about 10 cm in each layer.

The models were subjected to several shaking steps of horizontal excitation with an irregular base acceleration as typically shown in Fig. 3. The maximum amplitude of the base acceleration a_{max} was initially set 100 gals and increased at an increment of about 100 gals. At the shaking step when the model failed, the experiment was terminated.

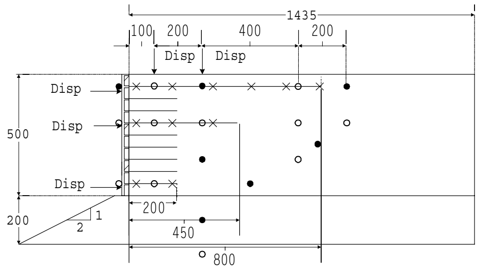
Air-dried Toyoura sand, having e_{max}=0.977; e_{min}=0.609; G_s= 2.64; and D_{50}=0.23 mm, was pluviated through air to form the backfill and subsoil layers at a void ratio of about 0.658 (D_r=90%). A grid of phosphor-bronze strips was used as the reinforcement for the reinforced-soil RW models with/without LD nails. Refer to Koseki et al. (1998) for the details of model preparation.



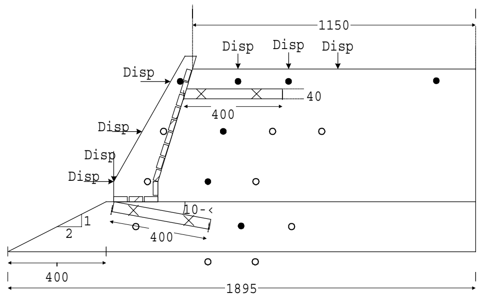
a) Leaning-type RW



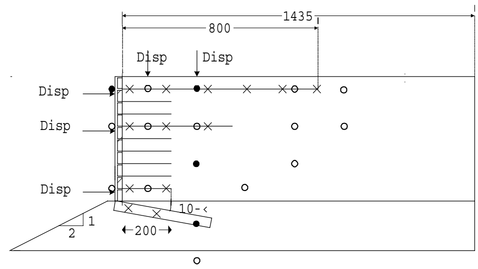
b) Cantilever RW



c) Geogrid-reinforced soil RW



d) Leaning-type RW with LD nails



e) Geogrid-reinforced soil RW with LD nails

● Horizontal and vertical accelerometers
○ Horizontal accelerometers
Disp Displacement transducers
▨ Two-component load cells
× Strain gages
All units in mm

Figure 1. Cross-sections of models

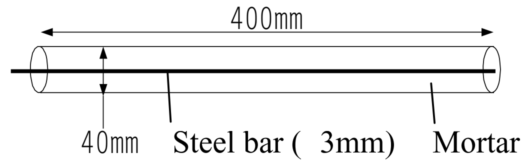


Figure 2. Model LD nail

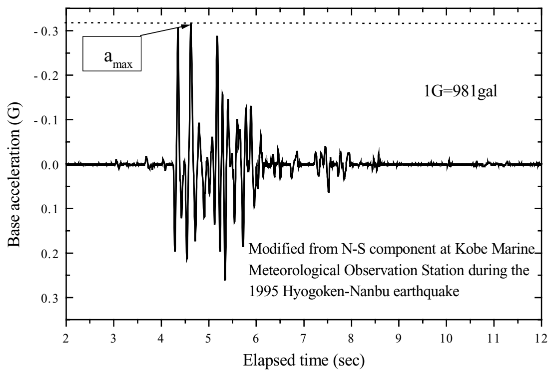


Figure 3. Typical time history of base acceleration

3 TEST RESULTS

3.1 *Failure pattern*

The deformation mode and failure pattern of five types of RW models are summarized bellow.

a) Leaning-type RW:
Figure 4 shows the failure pattern after the shaking at a_{max} equal to 794 gals. In the shaking step at a_{max} equal to 578gals, the first shear band (denoted as 1 in Fig. 4) was formed from the heel of the base footing of RW. In the step at a_{max} equal to 636 gals, the backfill began to deform largely due to formation of the second shear band (2 in Fig. 4). At a_{max} equal to 794 gals, the RW failed by the loss of bearing capacity, as clearly recognized by the large residual settlement of the toe of base footing into the subsoil.

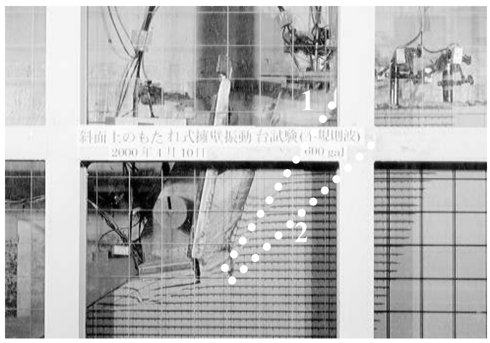


Figure 4. Failure pattern of leaning-type RW after shaking step of a_{max}= 794 gals

b) Cantilever RW:
Figure 5 shows the model after the shaking at a_{max} equal to 823 gals. In the step at a_{max} of 638 gals, two shear bands (1 and 2 in Fig.5) were formed all at once. The shear band 1 corresponds to the virtual back face of the RW as assumed in relevant stability analyses. During the shaking step at a_{max} of 823 gals, the RW was largely tilted, and a new shear band (3 in Fig.5) was formed.

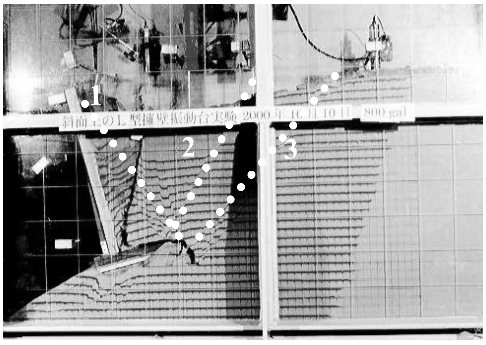


Figure 5. Failure pattern of cantilever RW after shaking step of a_{max}= 823 gals

c) Geogrid-reinforced soil RW:
In the shaking step at a_{max} equal to 889 gals, the first shear band (1 in Fig.6) was formed. At this shaking step, this shear band was partially formed somewhere between the end of 20 cm-long reinforcement and the end of 45 cm-long one. During the shaking step at a_{max} equal to 906 gals, the shear band 1 penetrated through the whole backfill, linked with the new shear band 2. The RW was tilted to the inward direction due to rotational sliding along these shear bands. At a_{max} equal to 944 gals, the shear band 3 was formed vertically along the end-points of six 20 cm-long reinforcements arranged at the lower part of RW. After the shaking step at a_{max} equal to 1098 gals, these shear bands could be observed clearly, as shown in Fig. 6

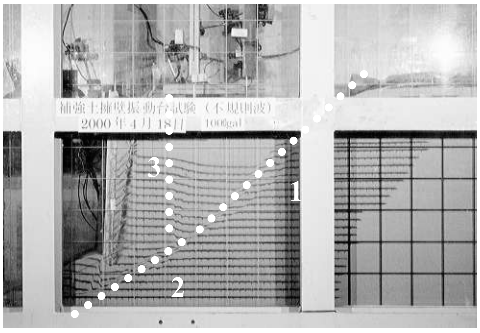


Figure 6. Failure pattern of the reinforced-soil RW after shaking step of a_{max}= 1098 gals

d) Leaning type RW with LD nails:
In the step at a_{max} of 1331 gals, three shear bands in the backfill (1,2 and 3 in Fig. 7) and another shear band 4 just below the footing of RW were formed. The shear bands in the backfill developed from the upper part of backfill and ended somewhere above the nails located beneath the footing, as seen from Fig. 7. After the test, the nails were found to survive without cracking.

Figure 7. Failure pattern of leaning-type RW with nails after shaking step of a_{max}= 1331 gals

e) Geogrid-reinforced soil RW with LD nails:
In the step at a_{max} equal to1464 gals, two shear bands in the middle of backfill (1 and 2 in Fig. 8) and another shear band in the area farther from the RW (3 in Fig. 8) were formed. All the shear bands didn't penetrate through the backfill to its top surface. According to the observation of the colored sand layers arranged in the central part of the backfill, after the step at a_{max} equal to 1577 gals, shear band 2 could not be recognized clearly. Therefore, it is likely that this shear band was formed only at the side, not the complete one. At a_{max} equal to 1577 gals, two shear bands 1 and 3 developed further to penetrate through the backfill. The shear band 1 was formed from somewhere at the end of 20 cm-long reinforcement layers to the top surface of the backfill grazing the end of 80cm-long reinforcement. While another shear band 4 was formed just bellow the RW, all the shear bands were not connected to the each other due likely to the existence of nails, as shown in Fig. 8. All the four nails didn't suffer any crack.

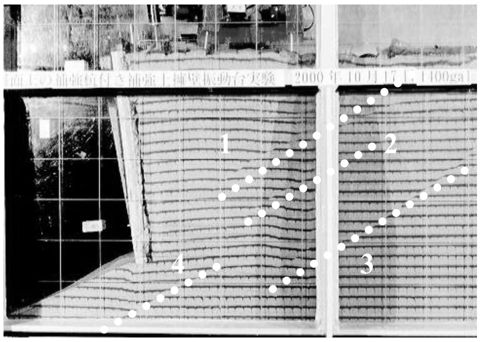


Figure 8. Failure pattern of reinforced-soil RW with nails after shaking step of a_{max}= 1577 gals

3.2 *Residual displacement of wall*

Figure 9 shows the relationship between seismic coefficient k_h, defined as a_{max}/g, and the residual horizontal displacement d_{top} measured near the top of the wall. To compare the behaviors of a pair of RW models of the same type (i.e., leaning type or cantilever or reinforced soil) constructed either on slope or on level ground, the test results on RWs constructed on level ground (Watanabe et al., 2001) corresponding to those performed in the present study, were plotted together. The results on slope were shown with triangle symbols, while the results on level ground were shown with square symbols.

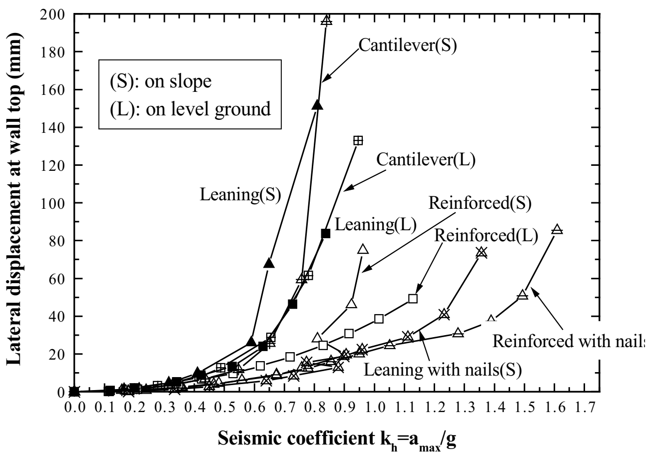


Figure 9. Accumulation of residual displacement at the top of several types of RWs ((S):on slope, (L):on level ground)

By comparing the behaviors of a pair of RW models of the same type (i.e., leaning type or cantilever or reinforced-soil) constructed on slope and level ground, it is seen that the seismic stability of the respective RW model on slope was much lower than the one on level ground. Irrespective of the subsoil conditions, the conventional RWs (leaning type and cantilever) exhibited brittle failure at relatively low base acceleration. Despite a relatively short reinforcement (40% of the wall height), the reinforced-soil RW on level ground showed ductile behavior. On the other hand, the reinforced-soil RW on slope showed less ductile behavior, due to premature formation of shear band as discussed later.

The leaning type and reinforced-soil RWs with LD nails exhibited substantially higher seismic stability than those without LD nails, showing small displacements even when subjected to a base acceleration higher than 1g.

3.3 *Resistant forces of RWs*

The differences in the seismic behaviors of RWs between conventional and reinforced-soil RWs, and between those on slope and level ground are considered to depend on the mechanism of mobilizing resistance against seismic loads (i.e. dynamic earth pressure and seismic inertia force). That is, conventional RWs resist by the bearing capacity at the bottom of base footing, reinforced-soil RWs resist by the tensile forces of reinforcement layers.

Figure 10 shows the relationship between the position and the magnitude of resultant normal force acting at the bottom of base footing of conventional RWs. At lower seismic loads, relatively large resultant normal force could be mobilized near the toe of footing. However, at higher seismic loads, the magnitude of the resultant normal force was reduced and its position moved toward the heel due to a local bearing capacity failure at the toe. This bearing capacity failure resulted in a less seismic stability of conventional RWs. In addition, by comparing the behaviors of a pair of RW models of the same type, it can be seen that the magnitude of the resultant normal force of RWs on slope was noticeably smaller than that on level ground, with its position located nearer the heel. These different behaviors supported the fact that RWs on slope were less stable than those on level ground.

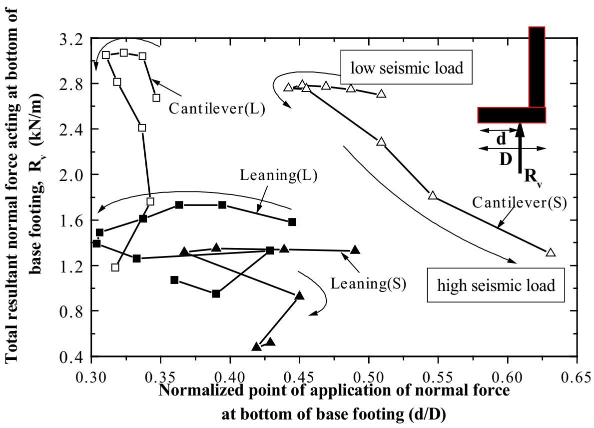


Figure 10. Relationship between magnitude and position of normal force at bottom of base footing

Figure 11 shows the relationship between the lateral displacement at top of wall d_{top} and tensile force of reinforcement. The larger the wall top displacement became, the more tensile force was mobilized. This resistant mechanism resulted in the ductile behavior of reinforced-soil RWs with a high seismic stability. The tensile force of reinforcement with the RW on level ground could increase continuously, while that with the RW on slope suddenly started decreasing when the d_{top} value became about 18 mm. This behavior was due to the formation of shear bands 1 and 2 (Fig. 6).

Such effects of LD nails are due to increasing the bearing capacity and preventing the formation of continuous shear band. Based on these results, it was inferred that nailing could be one of the best ways to stabilize existing leaning-type RWs on slope, while reinforced-soil RWs with nails could be the most stable ones as newly constructed RWs on slope.

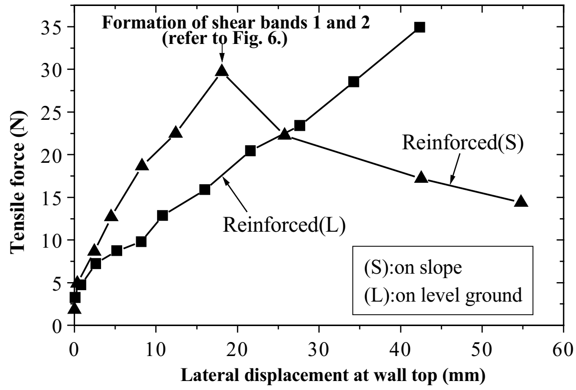


Figure 11. Relationship between tensile force of reinforcements and wall displacement

4 CONCLUSIONS

Results from model shaking tests can be summarized as follows.

- The early formation of shear band resulted in a less seismic stability of RWs on slope than those on level ground. The nailing prevented the formation of a full shear band effectively.
- Conventional RWs on slope exhibited brittle behavior due to a local bearing capacity failure at the toe, which occurred more easily than those on level ground.
- Reinforced-soil RW on slope showed less ductile behavior than that on level ground, due to formation of a full shear band in unreinforced backfill and subsoil.
- The nailing could be one of the best ways to stabilize existing leaning-type RWs on slope, and reinforced-soil RWs with nails could be the most stable ones as newly constructed RWs on slope.

REFERENCES

Koseki, J., Munaf, Y., Tatsuoka, F., Tateyama, M., Kojima, K. & Sato, T. 1998. Shaking and tilt table tests of geosynthetic-reinforced soil and conventional-type retaining walls, *Geosynthetic International* 5(1-2): 73-96.

Koseki, J., Watanabe, K., Tateyama, M. & Kojima, K. 2001. Seismic earth pressures acting on reinforced-soil and conventional type retaining walls, In Ochiai et al. (eds.), *Landmarks in Earth Reinforcement* 1: 393-398. Balkema.

Tatsuoka, F., Koseki, J. & Tateyama, M. 1997. Performance of reinforced soil structures during the *1995 Hyogo-ken Nanbu Earthquake,* In Ochiai et al. (eds.), *Earth Reinforcement* 2: 973-1008. Balkema.

Watanabe, K., Tateyama, M., Kojima, K. & Koseki, J. 2001. Irregular shaking table tests on seismic stability of reinforced-soil retaining walls, In Ochiai et al. (eds.), *Landmarks in Earth Reinforcement* 1: 489-494. Balkema