Landmarks in Earth Reinforcement, Ochiai et al. (eds),
© 2001 Swets & Zeitlinger, ISBN 90 2651 863 3

Study on reinforcement method for seismic slope stability

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ABSTRACT: In this paper, a new reinforcement method including rock bolts and rope net is used to stabilize the slopes during an earthquake. The behavior of a slope model, during cyclic loadings, is investigated by utilizing shake table tests and numerical simulation obtained from finite element analysis. Both experimental and numerical results show the efficiency of the reinforcement method on the seismic response of the slope by reducing the maximum displacement of the model, and preventing from rapid sliding failure. As well as good slope stability, the cost of construction in this method is cheaper than other methods because of no need to remove vegetation and to scrape the ground surface, which makes it efficient and ecological in practice.

1 INTRODUCTION

The city of Kobe in JAPAN was severely damaged during the 1995 earthquake. The damage included land slides and slope failures. In a project, funded by Forestry Agency, the Hyogo Prefecture investigated the stability of slopes during an earthquake through several experimental and analytical procedures. The main purpose of the project was to determine the failure mechanism of the slopes during an earthquake and investigate a new method to stabilize them against relatively large earthquakes. In this new method, rock bolts and rope net are used as reinforcement to stabilize the slopes against sliding and fracture. As well as good slope stability, the new reinforcement method used in this project has some features in terms of economy and ecology. The cost of construction in this method is less than other methods. In order to set up and install the reinforcement, it is not necessary to remove the vegetation and to scrape the ground surface, which makes it efficient and ecological in practice.

In this paper, a part of this project concerning experimental results and numerical analysis of the slopes with and without reinforcement is introduced. At first the experimental model and details of the reinforcement used in the shake table test are introduced and then the numerical finite element idealization is presented. Finally, the experimental and analytical results are compared with each other so that the role of rock bolts and rope net during cyclic loadings is investigated.

2 EXPERIMENTAL MODEL

The model of a slope, used for the present experiment is shown in Figure 1 and the section of the slope model is presented in Figure 4. It has about 12.00m long, 3.00 m high and 5.00 m wide. The angle of slope is 45 degree. The thickness of the soil placed on the steel platform is 1.20 m. As shown in Figure 4, the experimental model consists of two parts. The first part, which is located at the right hand side of Figure 4, is the reinforced soil with rock bolts and rope net. The second part is the soil without reinforcement. This makes it possible to compare the experimental results of soil with and without reinforcement at the same time. Figures 2 and 3 show the two inclined surfaces of the model with and without reinforcement. As for the reinforced part, the heads of rock bolts are connected through a fiber mesh of rope net that has covered the surface of the slope. The bottoms of rock bolts are fixed to

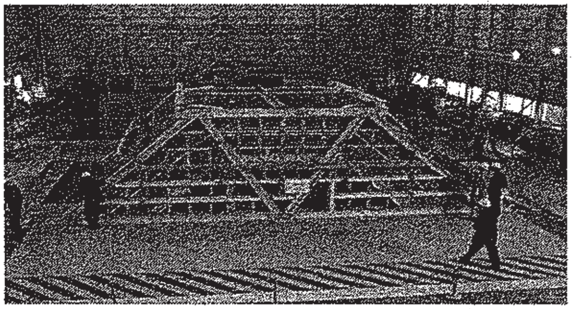

Figure 1. Experimental model of slope.

the foundation. The longitudinal ropes are fixed to the platform at the bottom and to the centerboard.

The soil used for the model is weathered granite. The rock bolts are made of aluminum with a length of 1200 mm and a diameter of 5.7mm. The spacing between the rock bolts is 40 cm. Rope net is made of polyester with a diameter of 0.8 mm and a mesh size of 10x10cm. The shake tests start with the maximum horizontal acceleration of 150 Gal and repeat with an increment of 50 Gal for each step until sliding failure occur. Each step takes about 20 seconds. The input motion consists of sin waves with the frequency of 3 Hz. Figure 5 shows the sample of input motion with the maximum acceleration of 250 Gal. The acceleration starts from zero and gradually increases to a maximum specified value in 5 seconds. Then it continues for 10 more seconds with the maximum acceleration and finally diminishes to zero in 5 seconds.

Figure 2. Inclined surface of slope without reinforcement.

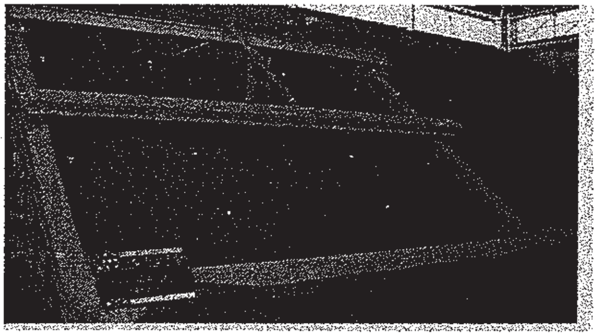

Figure 3. Inclined surface of slope with reinforcement.

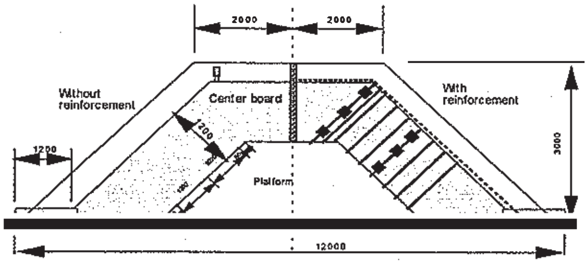

Figure 4. Section of the slope model.

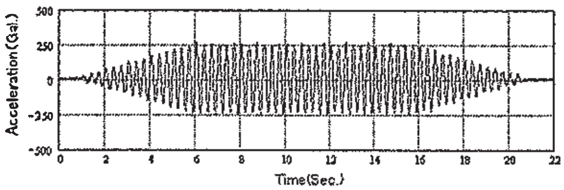

Figure 5. Horizontal input motion at the shake table.

3 FINITE ELEMENT IDEALIZATION

3.1 *Model description*

The finite element model of the slope and reinforcement are shown in Figures 6, 7. Soils are modeled with two-dimensional solid elements. Rock bolts and rope nets are modeled using three-dimensional beam and two-dimensional truss elements. Since the rope net can not tolerate axial compression forces, the material for the rope net has no stiffness in compression.

3.2 *Basic analysis parameters*

The basic analysis parameters used for the soil material are shown in Table 1. These values have been obtained from laboratory tests. The nonlinear behavior of the soil is modeled using the theory of multi-

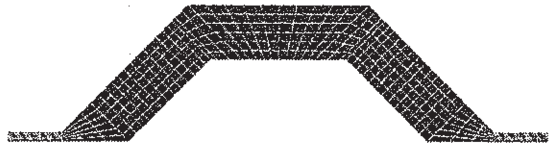

Figure 6. Finite element model of slope.

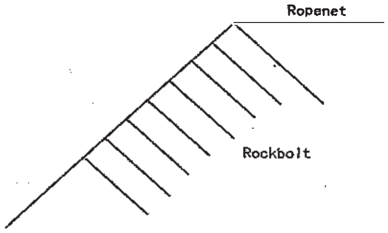

Figure 7. Finite element model of reinforcement.

Table 1. Soil material property in finite element analysis.

Material property of soil			
No.	Parameter	Quantity	Unit
1	Shear modulus	2.35E+07	Pa.
2	Bulk modulus	7.63E+07	Pa.
3	Weight density	1.60E+03	Kg./m^3
4	Cohesion	0.90+E04	Pa.
5	Internal friction angle	31.0	Degree
6	Poisson's ratio	0.37	—

Table 2. Material property of rock bolt.

Material property of rock bolt			
No.	Parameter	Quantity	Unit
1	Young modulus	7.00E+10	Pa.
2	Poisson's ratio	0.345	—
3	Weight density	2.70E+03	Kg./m^3
4	Cross sectional area	2.55E-05	m^2
5	Second moment of inertia	7.95E-11	m^4

Table 3. Material property of rope net.

Material property of rope net			
No.	Parameter	Quantity	Unit
1	Young modulus	130E+10	Pa.
2	Poisson's ratio	0.458	—
3	Weight density	0.90E+03	Kg./m^3
4	Cross sectional area	5.02E-07	m^2

yield plasticity (Prevost 1989). As for the rock bolts and rope nets, the material properties are shown in Tables 2, 3.

3.3 *Boundary conditions*

In order to model the slippage between rock bolts and soils during the analysis, nodal link elements are used at the contact points of beam and solid elements (Prevost, 1998). One nodal link element connects two nodal points either in translation or in rotation and is defined with a linear/non-linear stiffness. These nodal link elements enable local non-linearity between rock bolts and soil during excitation, and give smooth transition of forces acting in two different materials. The heads of rock bolts are directly connected to the rope net and the bottoms of rock bolts are fixed to the foundation. These connections are joined without nodal link elements. The model has vertical supports and recieves horizontal input motion uniformly at the base.

4 EARTHQUAKE RESPONSE OF THE SLOPE

To compare the experimental and numerical response of the model, the displacements at the crest are measured during the experiments. An illustration of the experimental results is shown in Figure 8. At the level of 250 Gal, a relatively large deformation is observed at the top of the slope without reinforcement with some local cracks. At this level, due to the effect of rope net and rock bolts, the deformation of reinforced part is still small and no cracks are observed at the crest. When the input acceleration is stepped up to 300 Gal, a sliding failure occurs in the slope without reinforcement. The slope rapidly deforms, along with large cracks at the crest. At this level, some small cracks appear at the crest of reinforced side but the displacements of slope are still small. Large cracks occur in reinforced soil at the level of 350 Gal. Large deformation is observed at the top of the slope but rapid sliding failure is prevented.

The nonlinear dynamic analysis of the model is performed using a computer program named DYNAFLOW (Prevost, 1998). DYNAFLOW is a finite element analysis program for linear, non-lincar, two and three-dimensional systems. It provides several material models including pressure dependant geomaterials with different types of hardening rules. In the present analysis, nonlinear behavior of soil elements is based on the theory of multi-yield plasticity

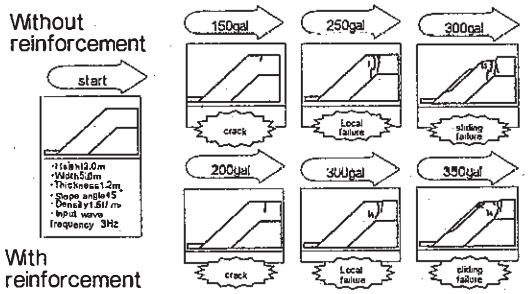

Figure 8. Illustartion of shake table test results.

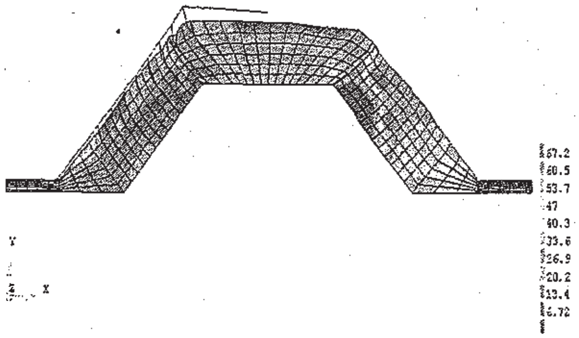

Figure 9. Mobilized phi and deformed shape of slope.

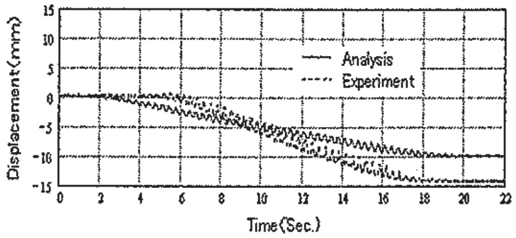

Figure 10. Vertical displacement time history of crest (no reinforced slope).

with a kinematic hardening rule, modeling the stress-strain behavior in cyclic loadings at both low and high stress levels (Prevost, 1989).
In the present analysis, maximum input acceleration is 250 Gal. Figure 9 shows the deformed shape with mobilized phi contours of the model at time 10 seconds. As expected, the deformation of the slope without reinforcement is larger than reinforced side. The result of the laboratory triaxial test gives the internal friction angle of 31 degrees and the cohesion of 0.9E+04 Pa. The mobilized phi value larger than the internal friction angle means unstable state. As seen in Figure 9, the slope without reinforcement has larger values of mobilized phi, which shows less stable state than the reinforced side. The vertical displacement time history of the crest in the no reinforced slope is shown in Figure 10. The solid linerepresents the analysis results and the dot line represents the measured displacement in the experiments. Figure 11 also compares the displacement time history of crest in the reinforced slope between the analysis and the experiment.

Table 4 compares the maximum vertical values of displacements at the crest of slopes with and without reinforcement. Due to the reinforcement of rock bolts and rope net, there is an effect on decreasing the maximum displacement response.

5 CONCLUSIONS

The results of the experiments and the numerical simulation are concluded as follows.

1) A new method of rope net and rock bolts used for reinforcement to stabilize the slopes during an earthquake has an effect on decreasing the displacement response during cyclic loadings.

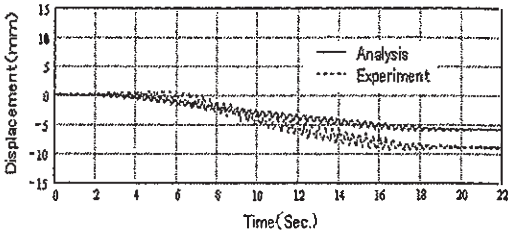

Figure 11. Vertical displacement time history of crest (reinforced slope).

Table 4. maximum vertical displacement of crest.

Maximum vertical displacement of crest(mm)		
Case	Experiment	Analysis
Without reinforcement	−14.27	−10.11
With Reinforcement	−9.05	−6.23

2) There is reduction in mobilized phi angle of the reinforced side, which implies more stability than the side without reinforcement.

3) The non-linear dynamic analysis gives close results to the experiments regarding to the vertical displacement of the crest.

6 ACKNOWLEDGEMENTS

The authors are very thankful to the members of the advisory committee, Prof. Okimura and Prof. Tanaka of Kobe University, Prof. Ohmachi of Tokyo Institute of Technology, Dr.Matsuura of Forestry and Forest Products Research Institute, Dr. Sugano of Port and Harbour Research Institute, and Dr.Goto of Ohbayashi Co., Ltd. for their expertise and valuable advises.

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