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Soheil Razavi
DIA Consultants Co., Ltd., Japan

Hiroyuki Kimura
DIA Consultants Co., Ltd., Japan

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Soheil Razavi
DIA Consultants Co., LTD.,
2-272-3, Yoshino-Cho, Omiya-Shi,
Saitama, 330-8660 JAPAN

Hiroyuki Kimura
DIA Consultants Co., LTD.,
2-272-3, Yoshino-Cho, Omiya-Shi,
Saitama, 330-8660 JAPAN

ABSTRACT

In this paper the behavior of an artificial slope, during a cyclic loading, is investigated by utilizing shaking table test and numerical simulation obtained from a finite element analysis. The effects of rock bolts and rope nets, used to stabilize the slope during earthquake, are investigated in several experimental and analytical cases. The slippage between rock bolt and soil is simulated by a nodal link element, placed at the contact area of rock bolt and soil. Using rock bolts and rope nets as reinforcement, affect the response of the model by reducing the maximum displacement of the slope along with a considerable decrease in maximum tensile stress. The developed cracks at the top of slope are also modeled with link element. When the cracks open, tensile stress can not develop across the opening and a tensile stress release may occur in that area which results in a redistribution of internal stresses in the slope.

INTRODUCTION

The city of Kobe in JAPAN was highly damaged during the 1995 earthquake. A part of these damages were huge land slides and slope failures. In order to investigate the stability of slopes during earthquake, several experimental and analytical procedures were adopted. The main purpose of the experiments was to determine the failure mechanism of the slopes during earthquake and investigate the methods used to stabilize them against relatively high earthquakes. In the present work, rock bolts and rope nets are used as reinforcement to stabilize the slopes against sliding and fracture. As well as reinforcement, the shape of the slope itself has an important role on the displacement response and stress concentration at the edge of the slope. Result of the experiment on slopes with sharp and rounded shape edges clarifies the shape effects on the seismic response of the slope.

In this paper, a numerical finite element analysis is performed on the slope model. At first, the effects of rock bolts and rope nets are considered in a two dimensional model considering the slippage between the rock bolts and soil elements. The effect of shape of the slope is then considered in a sharp and rounded finite element model and the results are compared with each other. Finally, the cracks developed at the top of slope are simulated with a three-dimensional link element and the effect of the cracks on the seismic response of the slope is investigated.

EXPERIMENTAL MODEL

Model description

The artificial model of slope, used for the experiment is shown in photos 1 and 2. It has a length of about 3.4m and the height of 1.5 m. The width of the model is 1.5 m. and the angle of slope is 45 degree. Photo 3 shows the inclined surface of the reinforced slope with combination of rock bolt and rope net. The head of rock bolts is connected to the rope nets and bottom of rock bolts is fixed in to the foundation. The longitudinal rope nets are fixed to the foundation at both ends. Fig.1 shows a schematic map of the slope with reinforcement arrangement used in experiment. In this figure, dot line represents the rope net and solid line represents the rock bolts. Photos 4, 5 show the sample of the rock bolt and rope net used as the reinforcement in the experiment. The length of the rock bolt is about 60 cm and the spacing between rock bolts is 20 cm. The mesh size of the rope net is 5x5 cm.
The material used for the soil model is decomposed weathered granite. The rock bolt material is aluminum and rope nets are made from polyester. Table-1 shows the material and size of the reinforcement used in the present experiment.
The maximum horizontal acceleration starts from 50 Gal and increases by an increment of 50 Gal in several steps, until failure occurs. Each step takes about 15 seconds and the frequency of the input acceleration is 5 hertz. Fig. 6 represents the sample of input acceleration at the step with maximum acceleration of 250 Gal.

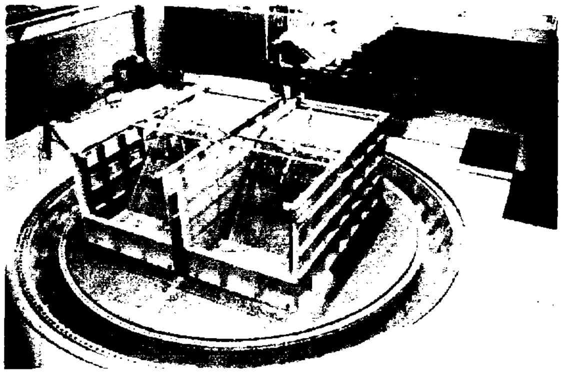

Photo-1: Experimental model

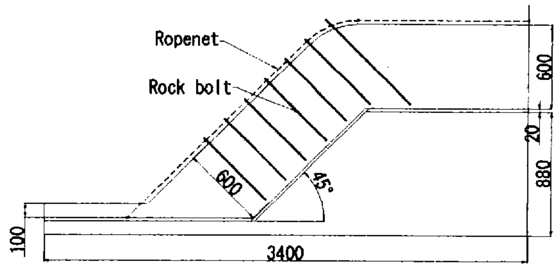

Fig. 1: Reinforcement in slope model

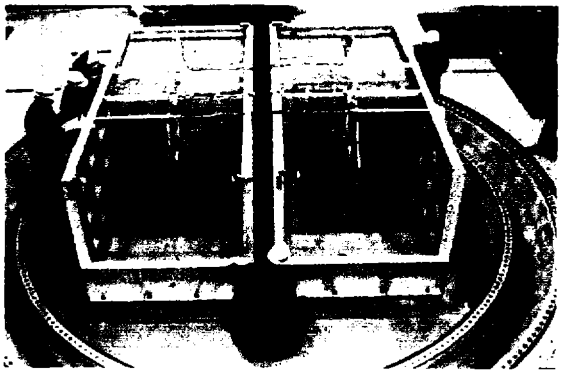

Photo-2: Experimenalt model

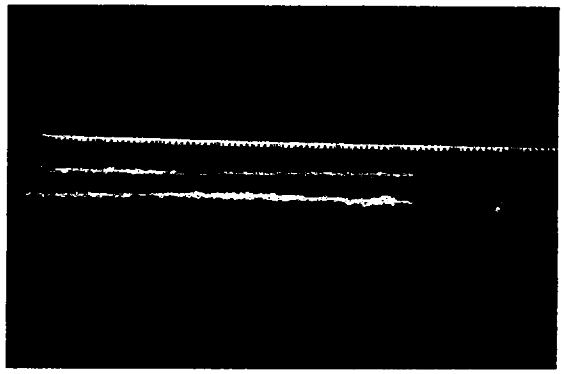

Photo-4: Rock bolt used as reinforcement in experiment

Photo-3: Reinforced slope with rock bolt and rope net

Photo-5: Rope net used as reinforcement in experiment

Material used for reinforcement			
Name	Material	Length (mm)	Diameter (mm)
Rock bolt	Aluminum	600	3
Rope net	Polyester	—	0.8

Table-1: Reinforcement material in experiment

FINITE ELEMENT IDEALIZATION

Model description

Finite element models of the soil are shown in figures 2, 3. In Fig. 2 the finite element mesh has a sharp edge at the top of slope and is named as sharp model. In round model, shown in Fig. 3, the edge at the top of the slope has a rounded shape. The finite element model of rock bolts and rope nets is shown in Figs 4, 5. Rock bolts are modeled using two dimensional beam elements and rope nets are modeled with two dimensional truss elements. Since the rope nets can not tolerate axial compression force, the material for rope net is supposed to have compression cut off property.
In order to model the slippage between rock bolt and soil during the analysis, a nodal link element has been used at the contact point of rock bolt and solid element [Prevost, 1998]. The nodal link element connects two nodal points either in translation or in rotation. The element can be defined, using two nodes and a single directed axis with a linear/non-linear stiffness. In this situation the bolts and soil elements have the capability to separate from each other during the excitation which is in agreement with actual situation.

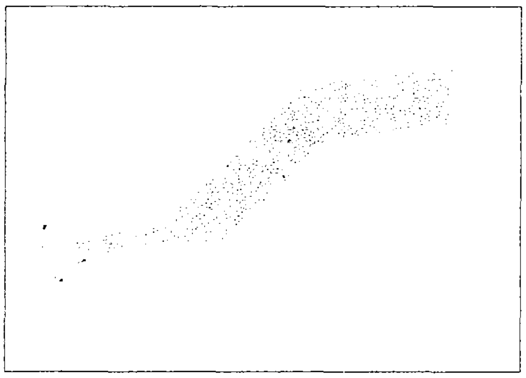

Fig. 2: Finite element mesh of sharp model

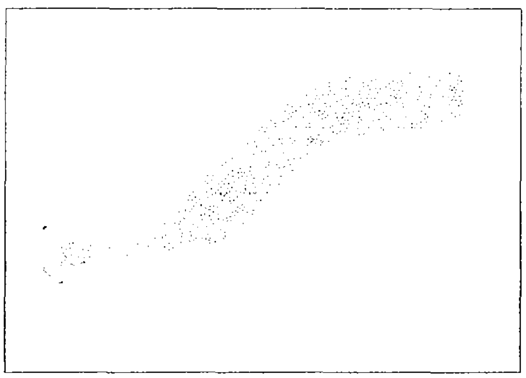

Fig. 3: Finite element mesh of round model

Basic analysis parameters

The basic analysis parameters used in the analysis for soil material is shown in Table-2. These values have been obtained from laboratory tests. The nonlinear material behavior of soil is modeled using Drucker-Prager criterion [Chen, 1982]. As for the rock bolts and rope nets, the material properties are shown in Tables 3, 4. The rope nets can not tolerate any compression stresses and in the whole analysis the material is supposed to be compression cut off.

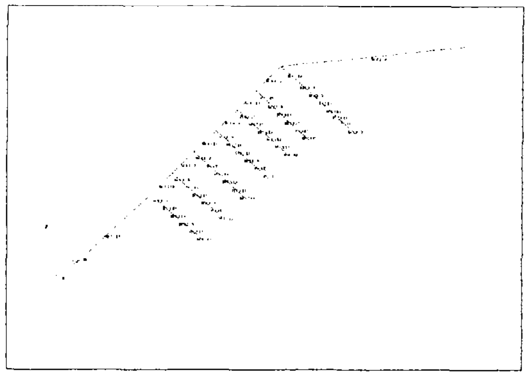

Fig. 4: Rock bolts and rope nets in sharp model

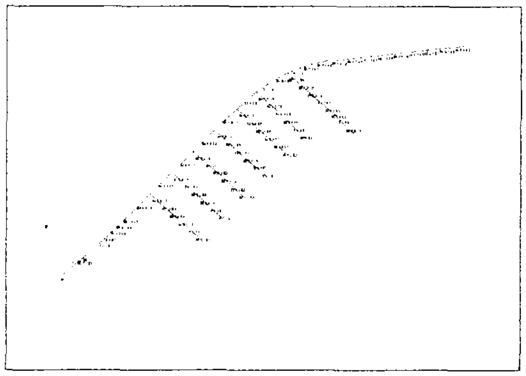

Fig. 5: Rock bolts and rope nets in round model

Input acceleration

Time history of input horizontal acceleration is shown in Fig. 6. The maximum input acceleration is 250 Gal with the duration of 15.00 seconds and frequency of 5 hertz.

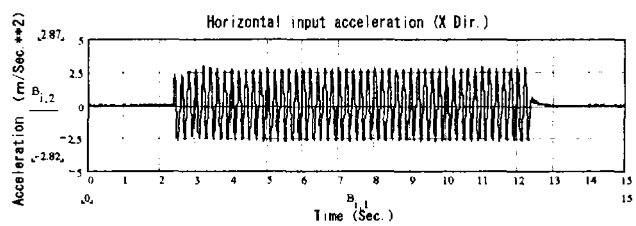

Fig. 6: Horizontal input acceleration in experiment

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.
4	Cohesion	0.80+E04	Pa.
5	Internal friction angle	31.0	Degree
6	Poisson's ratio	0.37	—

Table-2: Soil material property in FEM analysis

Material property of rock bolts			
No.	Parameter	Quantity	Unit
1	Young modulus	7.00E+10	Pa.
2	Poisson's ratio	0.345	—
3	Weight density	2.70E+03	Kg.
4	Cross section area	7.07E-06	m^2
5	Section inertia	2.00E-11	m^4

Table-3: Material property of rock bolt

Material property of rope nets			
No.	Parameter	Quantity	Unit
1	Young modulus	1.3E+10	Pa.
2	Poisson's ratio	0.458	—
3	Weight density	0.9E+03	Kg.
4	Cross section area	5.03E-07	m^2

Table-4: Material property of rope net

Boundary condition

The boundary condition of solid elements, rock bolts and rope nets are as below:

a) Solid element

At the contact surface of soil and foundation, the solid elements are fixed to the foundation.

b) Rock bolts

The head of Rock bolts are directly connected to rope nets and the bottom of rock bolts are fixed to the foundation. At the contact point of rock bolts and solid elements, a link element is used to model the possible slippage on that area.

c) Rope net

The rope nets are connected directly to the head of rock bolts and longitudinal rope nets are fixed to the foundation at both ends.

EARTHQUAKE RESPONSE OF THE SLOPE

The nonlinear dynamic analysis of the models was performed using DYNAFLOW program [Prevost, 1998]. DYNAFLOW is a finite element analysis program for linear, non-linear, two and three-dimensional systems. It provides several material models including pressure dependant geo-materials with different types of hardening rules. In the present analysis the material property used to model the nonlinear behavior of soil elements is based on Drucker-Prager criterion with a kinematic hardening rule [Prevost, 1998]. As for the shear stress-strain curve, the modified hyperbolic function including a power term is used. This function offers great versatility for modeling stress-strain behavior in cyclic loading at both low and high stress levels [Prevost, 1989]. The adopted nonlinear iteration procedure is Newton-Raphson method in which the tangent stiffness matrix is recomputed at every time step and at every iteration [Chen, 1982].

Response of sharp model with and without reinforcement

Figs 7 and 8 show the deformed shape of sharp model without and with reinforcement. Maximum displacement response of the sharp case without reinforcement is about 3.59mm and for the reinforced case is 2.55mm. Due to the effect of reinforcement there is a relatively considerable reduction in maximum displacement response of the sharp model.

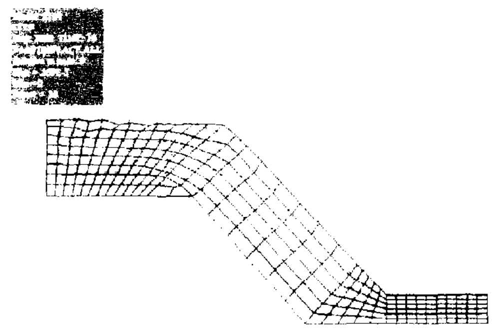

Fig. 7: Deformed shape of sharp model without reinforcement

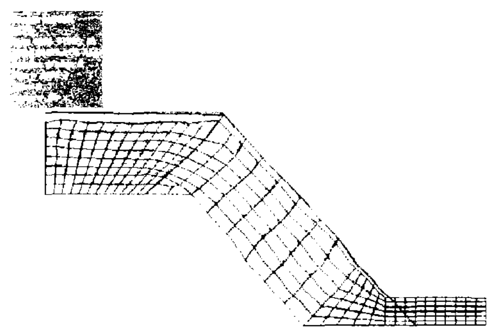

Fig. 8: Deformed shape of sharp model with reinforcement

Fig. 9 compares the displacement time history at the top of slope for the two cases in both horizontal and vertical directions. In this figure, solid line represents the response of the case without reinforcement and dotted line represent the

reinforced response. As was expected, there is a considerable reduction in displacement response of the reinforced case in both horizontal and vertical directions. As well, the residual displacement of reinforced case has become smaller which is in agreement with displacement response of the slope.
Table-5 summarizes the displacement at the top of slope for both models in horizontal and vertical directions.

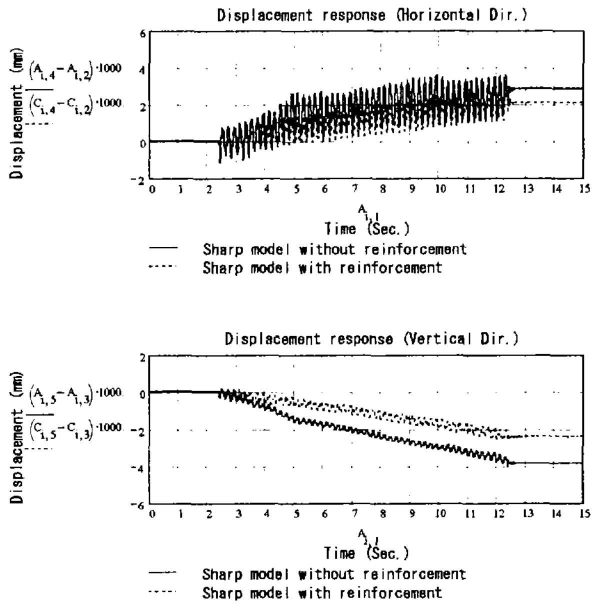

Fig. 9: Displacement response history with and without reinforcement for sharp case

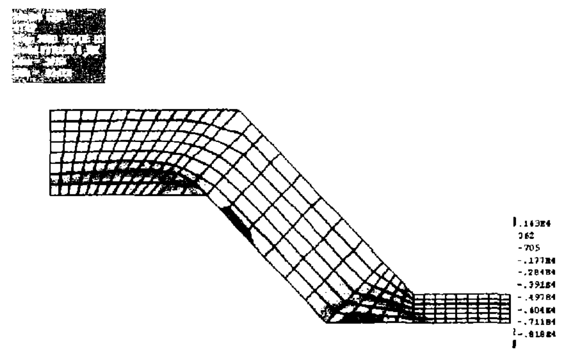

Fig. 10: Horizontal stress contour of sharp model without reinforcement

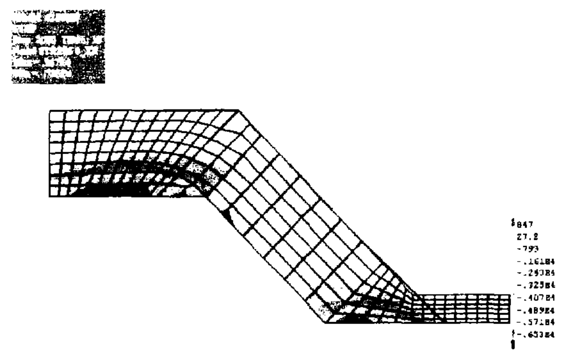

Fig. 11: Horizontal stress contour of sharp model with reinforcement

Displacement response at the top of slope				
Model	Horizontal displacement (mm)		Vertical displacement (mm)	
	Maximum	Residual	Maximum	Residual
With Reinforcement	2.91	2.07	-2.66	-2.42
Without Reinforcement	3.54	2.83	-4.15	-4.04

Table-5: Displacement response at the top of slope

Figs 10 and 11 show the horizontal stress contour distribution for sharp case without and with reinforcement. Comparing these two figures show that maximum tensile stress zones for both cases are located at the top of slope close to the sharp edge and at the inclined contact area of soil and foundation.
The maximum tensile stress of 0.134E+04 Pa. has reduced to 847 Pa. for reinforced case. This reduction in tensile stress, due to the effect of reinforcement, is in agreement with displacement response of both cases.

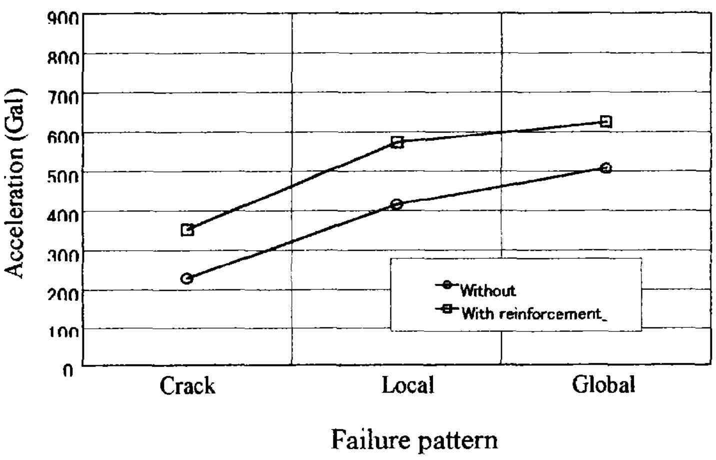

Fig.12: Failure pattern of sharp model with and without reinforcement

Fig. 12 compares the failure pattern of sharp model with and without reinforcement in experiment. The horizontal axis represents the failure pattern and the vertical axis represents the level of acceleration applied to the model during the experiment. The failure pattern is divided into three regions. The first one is named as crack region in which only the minor cracks may develop in some parts of the model without any major failure. The second one is local failure. In local failure, major cracks may occur in some parts and small damages may happen to the model. The last one is named as global failure, in which the cracks may spread in most parts of the model and some parts of the slope may slip down. As shown in Fig. 12, the level of acceleration correspond to each failure pattern of reinforced case is larger than the case without reinforcement. The efficiency of rock bolts and rope nets in stabilizing the slopes during earthquake is in agreement with results obtained from numerical analysis.

Response of sharp and round models without reinforcement

Results of experiment show that the shape of the top of slope affects the seismic response of the model. In order to investigate the shape effect on the response of the slope, two sharp and rounded models, as shown in Figs 2, 3, have been selected. Both models are without reinforcement and the only difference between them is the shape of the top part of slope. Fig. 13 compares the time history of displacement at the top of slope for sharp and round models. In this figure the solid line represents the displacement of sharp model and dotted line represents the round model. Maximum displacement response of the sharp case in horizontal and vertical directions is 3.54 and –4.15 mm respectively. The same response for round case is 2.48 and –3.98mm which is a relatively considerable decrease in displacement response of the slope. The same reduction has occurred for the residual displacement of the slope. This reduction in displacement response is in agreement with result of the experiment. Table-6 summarizes the maximum displacement and residual displacement of both cases.

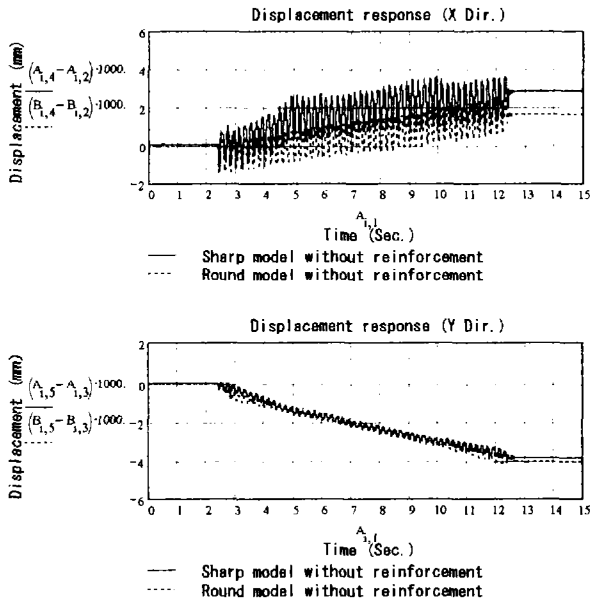

Fig. 13: Comparison between the time history of round and sharp models

Model	Displacement response at the top of slope			
	Horizontal displacement (mm)		Vertical displacement (mm)	
	Maximum	Residual	Maximum	Residual
Sharp model	3.54	2.83	-4.15	-4.04
Round model	2.48	1.61	-3.98	-3.87

Table-6: Displacement response at the top of slope

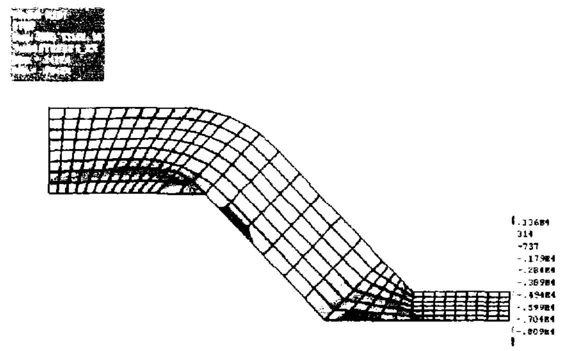

Fig. 14: Horizontal stress contour of round model without Reinforcement

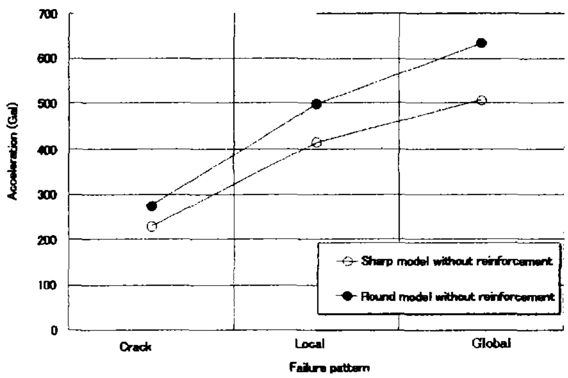

Fig. 15: Comparison between the sharp and round model failure patterns

Comparing the horizontal stress contours of the sharp and round cases in figures 10, 14 show that there is a decrease in maximum horizontal tensile stress in the round case. When the shape of the slope becomes round, there is a decrease in maximum displacement response and tensile stress of the slope.
Fig. 15 compares the failure pattern of the sharp and round models in experiment.
The maximum input acceleration for the present analysis is 250 Gal and at this level of acceleration we are in crack region without any major damage. As shown In Fig. 15, at a constant level of acceleration the damage of the sharp model is larger than round model. This phenomenon is in agreement with the

displacement and stress distribution results obtained from the analysis of both models.

Response of the crack model

Results of the experiment on the sharp model without reinforcement show that at 250 Gal some cracks may occur on the upper part of the slope, as shown in Fig. 16 in white line. One of the aspects of the present analysis is to model the developed cracks at that area and investigate their effects on the response of the slope. For this purpose, a 3 dimensional finite element model of the slope, as shown in Fig. 17, was established.
Finite element model of the cracks developed at the upper part of the slope is shown in Fig. 18. The cracks are simulated using a 3 dimensional link element [Prevost, 1998]. Link elements have been placed between the soil elements at predefined sections of the slope.
Figs 19, 20 represent the deformed shape and horizontal stress contour of crack model. Due to the joint opening at the top of the slope, maximum tensile stress in that area has been released and a stress redistribution has occurred inside the slope. When a crack occurs at some part of the model, the tensile stress can not develop across the opening and a tensile stress release, as shown in Fig. 20, may happen at that area. This phenomenon affects the stress distribution of the slope.
A new tensile stress zone is appeared on the surface of inclined part of the slope.
Each crack pattern may lead the analysis results to a new stress state. In order to simulate the real behavior of the slope during an experiment it seems to be necessary to make an accurate crack model based on the real crack pattern occurred during experiment.
Fig. 21 shows the location of cracks and failure pattern of the sharp model during the experiment. This figure represents the crack pattern at three levels of cracks, local failure and total failure of the model.

Fig. 16: Cracks developed at the top of slope

Fig. 17: Finite element model of slope

Fig. 18: Finite element model of cracks at the top of slope

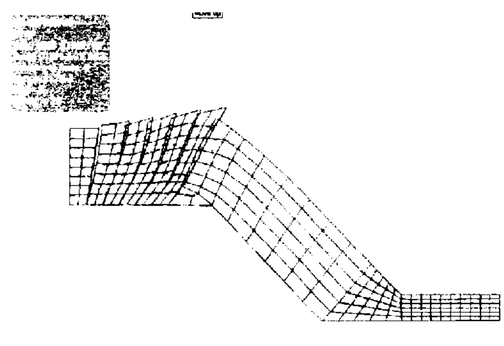

Fig. 19: Deformed shape of crack model

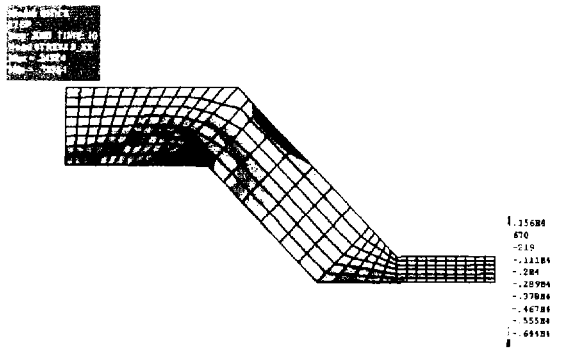

Fig. 20: Horizontal stress contour of crack model

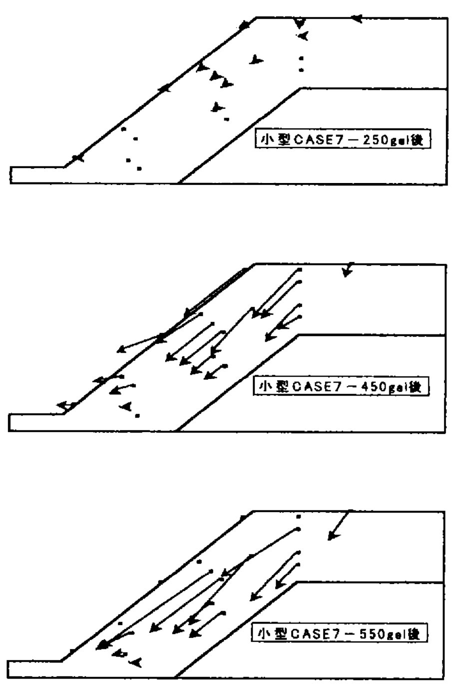

Fig. 21: Developed cracks and failure pattern in experiment

COMPARISON BETWEEN RESULTS

Fig. 22 compares the experiment and analysis displacement response of the sharp model at the top of slope in vertical direction.

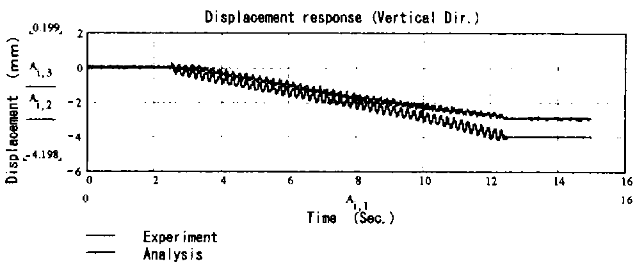

Fig. 22: Comparison between experiment and analysis result

Maximum calculated displacement in vertical direction is about −4.15 mm and maximum measured value during the experiment is -3.05mm. Although maximum values of the displacement are not the same, but we can conclude that general response of both cases are in agreement with each other. However, for a full comparison between the results, a complete parameter study seems to be necessary.

CONCLUSION

Based on the results of experiment on different models and numerical simulation obtained from finite element analysis, the following conclusions can be made.

1) Using rope nets and rock bolts as reinforcement, to stabilize the slopes during earthquake, has a considerable effect on the seismic response of the slope.
2) Results of the analysis on the sharp model with and without reinforcement show that rock bolts and rope nets affect the seismic response of the slope by decreasing the displacement response of the model in both horizontal and vertical directions. There is also a decrease in maximum residual displacement of the model in both directions.
3) There is a considerable reduction in maximum tensile stress of reinforced sharp model, which is in agreement with displacement response of the slope.
4) Results of the experiment and analysis on model with sharp and rounded shape show that rounded shape slopes has the smaller displacement response and can tolerate relatively higher level of acceleration. In rounded shape model the stress concentration at the top of slope is less than sharp case.
5) When the effect of the cracks at the top of the slope come in to the picture, there will happen a reduction in maximum tensile stress and a re-distribution of stresses in the slope.
6) Results of the calculated and measured vertical displacement at the top of slope are in agreement with each other. However, a parameter study analysis and material calibration seems to be necessary.

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