

## Shaking table tests of embankment models reinforced with geotextiles

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**ABSTRACT:** Large earthquakes have caused damage to soil structures such as earth dams, river dikes and reclamation dikes. To prevent this, the reinforcement of earth structures with geotextiles has been attempted. This paper describes the behavior of embankments reinforced with geotextiles (continuous fibers, geogrids) in shaking table tests using embankment models. The shaking table tests used small and large scale models constructed with sand. The test results confirmed that reinforcement with geotextiles greatly decreases settlement even of embankments and foundations constructed with loose sand. Some results of the shaking table tests were analyzed with the finite element method and compared with the test results.

### 1. INTRODUCTION

In this paper, shaking table tests were conducted on embankments constructed with sand and reinforced with two types of materials: continuous fibers and geogrids.

The method to reinforce sand with continuous fibers was developed in France. In Japan, with its frequent earthquakes, it is necessary to investigate the safety of this method during earthquakes. The method uses continuous fibers and covers the embankment surface with a mixture of continuous fibers and sand, and has successfully been used with existing embankments. With geogrids, geogrids are buried in the embankment, and this is suitable in construction of new embankments. Results of the shaking table tests showed that settlement of embankments reinforced with continuous fibers or geogrids was greatly reduced when compared with unreinforced embankments.

### 2. Reinforcement with continuous fibers

#### 2.1 Mechanical properties of reinforced sand

Prior to the shaking table test, the mechanical properties of sand reinforced with continuous fibers were investigated. The tests used two types of sand A in the mechanical tests and B; A was used, and both A and B in the Shaking table tests. Table 1 show the physical characteristics of the two sand types. The mechanical tests were drained triaxial compression and cyclic triaxial tests. The fibers mixed with the sand were polyester, with characteristics as shown in Table 2.

Table 1. Properties of sand

Sand	Specific gravity $G_s$	$D_{50}$ (mm)	$u_c$	Maximum and minimum void ratio'		Compaction properties**	
				$e_{max}$	$e_{min}$	$\rho_{dmax}$ ( $t/m^3$ )	$\omega_{opt}$ (%)
A	2.72	0.26	1.90	0.96	0.615	1.61	17.2
B	2.70	0.18	1.20	—	—	1.59	19.8

\*JSP(T26-1981) \*\*JISA1210(1.1.a)

Table 2. Properties of fibre

Standard	Tensile strength
Polyester	4.53 (gf/denier)
150 (denier*)	56.2 (kgf/cm <sup>2</sup> )
30 (filament)	36 (%)

\* 1 denier = 1g/9km

Both tests used 10cm diameter and 20cm high specimens. The specimens were a compacted mixture of constant weight ratio of fibers to sand. Fibers were mixed in, at a ratio of 0.2% of the dry weight of the sand. The density of specimens,  $\rho_d$ , was 1.52( $t/m^3$ ). The effective reinforcement was about 1% axial strain, and the difference between the principal stress of the unreinforced and reinforced sand increased. The strength parameter of the unreinforced sand is  $C' = 3.0(KPa)$  and  $\phi' = 38^\circ$ ,

while that of the reinforced sand is  $C' = 107(KPa)$  and  $\phi^i = 42^\circ$ . The effect of the reinforcement mainly showed in  $C'$ , and the difference,  $\Delta C$ , was about  $104(KPa)$ .

There are only small differences in the number of cycles, but the stress ratio of the reinforced sand is 35% greater than that of the unreinforced sand with 20 cycles, the number generally used to determine liquefaction strength. The results of the mechanical tests clearly show that reinforcement with continuous fibers is effective.

## 2.2 Shaking table test

The shaking table tests were performed to determine the effectiveness of reinforcement in embankment structures. The shaking table tests were of two types: a small scale model test of embankments and a large scale model test of foundations and embankments.

### 2.2a Small scale shaking table model test

Two types of sand, A and B, were used in the tests as shown in Table 1. The model in Figure 1 was constructed in a small box (68cm high, 40cm wide, 230cm long). Sand A was used in the (a), (b), and (c) tests in Figure 3, and sand B in the (a) and (c) tests. With sand A, reinforcement with dense sand was tested to determine whether the effect in Case (c) was due to the continuous fibers or the dense sand. In Case (a), the relative densities of sands A and B, the D-value ( $\rho_d/\rho_{dmax}$ ), were about 80%. The reinforced portions in (b) and (c) are the hatched parts in Figure 2. In (b), the sand was well compacted, and in (c), the sand was compacted and reinforced with continuous fibers, 0.2% of the dry weight of sand. The relative density of the sand in the reinforced portion, the D-value was above 95%. A sine wave with a frequency of 10 Hz was imposed for 10 seconds. The acceleration was increased in stages to about 100, 200, 400, and 600gal. Crest settlement was very small up to 400gal. At the maximum acceleration of 600gal, both the crest settlement and pore water pressure increased greatly, and the model without reinforcement collapsed. Figure 3 compares the settlement of the crest (D2) with sand A with and without reinforcement. Five seconds after loading, the settlement with continuous fibers reinforcement was approximately one-tenth that without reinforcement, and about one-third of the case reinforced with dense sand. Figure 4 compares the crest settlement with sand B. After loading for 10 seconds, the settlement of the case reinforced with continuous fibers is about one-fifth of the unreinforced case.

Next, the results of the large scale model tests will be detailed.

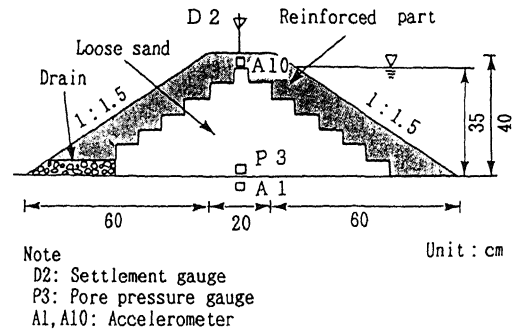


Figure 1. Small scale shaking table test model

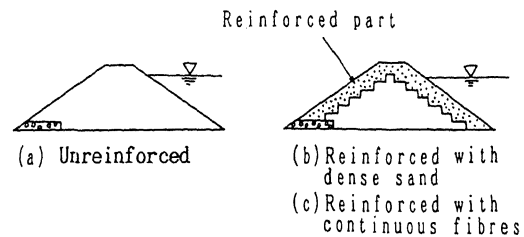


Figure 2. Case of the small scale shaking table test

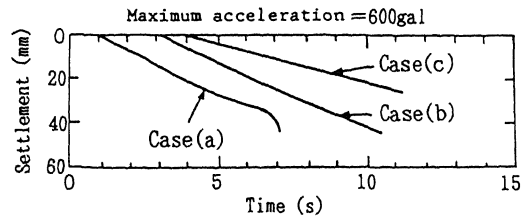


Figure 3. Settlement at crest D2 (sand A)

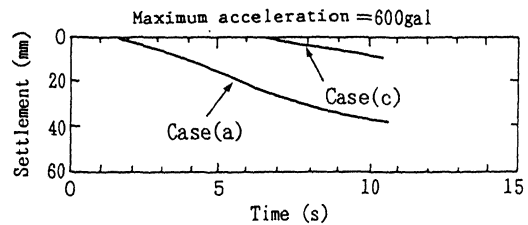


Figure 4. Settlement at crest D2 (sand B)

### 2.2b Large scale shaking table model tests

The model in Figure 5 was constructed on the large scale shaking table (1.5m high, 2.8m wide, 5.5m long). The model was about one-tenth of an earth dam where 1.5m settlement occurred at the Mid Japan Sea Earthquake in 1983. The grain size of the sand in the earth

dam was very similar to that used in the shaking table test. Figure 6 shows the three tests: (a) without reinforcement of both the dam and foundations (Case (a)); (b) reinforcement of only the dam with continuous fibers (Case (b)); and (c) reinforcement for the dam with continuous fibers and the foundations with model sheet piles (Case (c)). An outline of the models and the arrangement of instruments are shown in Figure 5. The foundations were made by depositing wet material in the shaking box with 30cm-deep water. The dam was also constructed by placing formwork and depositing wet material in the forms filled with water like the foundations. The relative density was about 50%. The reinforcement of the dam in Case (b) consisted of two fibers from a four-hole nozzle bundled into eight fibers, which were pushed out by high pressure water and mixed with sand injected through a hose via a hopper. The reinforced parts were compacted with a small-size vibrator, and the continuous fibers comprised 0.2% of the dry weight of the sand. In Case (c), a sheet pile model of 15cm-thick acrylic plate was placed from the top of the dam wall to the base of the foundations in Case (b).

A 3Hz sine wave was imposed for 10 seconds, and the maximum input acceleration was 150 and 250gal. Figure 7 shows the resonant curve of the crest in Case (a) (without reinforcement) with an input sine wave of 20 gal. The response increases about 16 times with a frequency of 22Hz. With a maximum input acceleration of 150gal, the crest settlement was 30mm in Case (a), but there was little settlement in Cases (b) and (c). At the maximum input acceleration of 250gal, loading for 10 seconds resulted in crest settlement of more than 70mm in Case (a), but only 40mm in Case (b) and about 26mm in Case (c). In Case (b), the crest settlement was 60% less than without reinforcement. In Case (c), the settlement decreased less because the sheet pile moved, and was of no use, however, settlement was still 40% less than without reinforcement and 60% less than Case (b). The effectiveness of reinforcement together with sheet piles may be very good.

Figure 9 shows the pore water pressure at P12 in the three cases. The pore pressure starts to increase immediately in Case (a), but there is little increase until about 3 seconds of loading with (b) and (c). This is caused by the reinforcement preventing an initial increase in pore water pressure and less settlement of the crest. When the pore water pressure increase to the effective overburden pressure, settlement with reinforcement does not increase as rapidly as without unreinforcement. This would indicate that reinforcement with continuous fibers or together with sheet piles may greatly decrease settlement of existing embankments on liquefiable foundation. Though the result from the models cannot be applied directly to actual structures, this method may offer an advantage

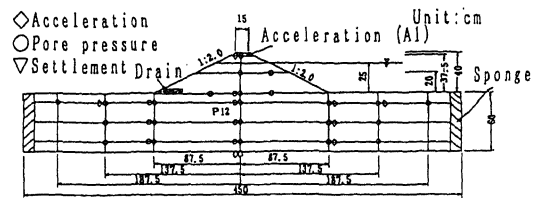


Figure 5. Large scale shaking table test model

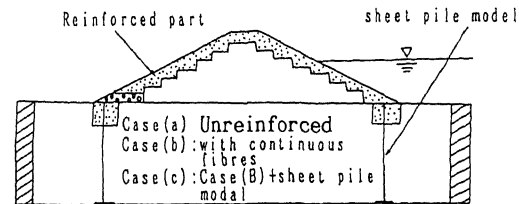


Figure 6. Case of the large scale shaking table test

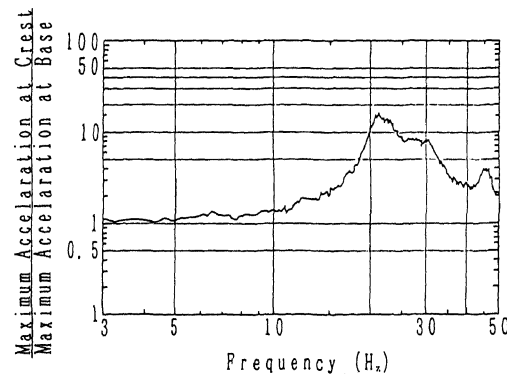


Figure 7. Resonant curve (case (a))

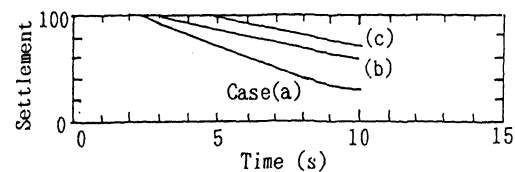


Figure 8. Settlement at D1 (Max. ACC.=250gal)

geous construction method providing earthquake resistance for existing earth structures.

### 3. Reinforcement with geogrids

The effectiveness of geogrids was investigated with the shaking table tests using the large and small scale models assuming a newly-constructed embankment enclosing upperstream water.

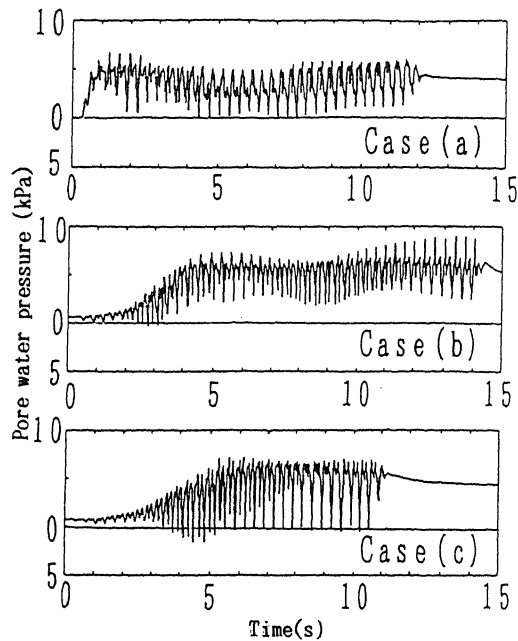


Figure 9. Time history of pore water pressure at P12 (case(a), (b), (c))

### 3.1 Small scale shaking table test

In the small scale shaking table test, the embankment was to be constructed with rock on the upperstream side and loose sand down stream. Sand A was used in the test, and Figure 10 shows an outline of the small scale model and the arrangement of instruments. The model was 2m long, 43.3cm high, and 40cm wide.

The tests particulars are shown in Table 3. Geogrids were placed horizontally in the embankment, and 0, 3, 4, or 6 were used to determine differences in reinforcement effectiveness.

The model was constructed by depositing wet sand with underwater deposition to obtain the required density. The input wave was a sine wave with 3Hz frequency, and the maximum input acceleration was about 220, 350, or 450gal. Resonance tests prior to the shaking test established no resonance frequency between 1 - 50Hz. As the model was relatively small, geogrids with low rigidity were used in consideration of scale effects. The density of the rock portion was  $1.90t/m^3$ , and the relative density of the sand portion was  $D_r = 40-50\%$ . Table 5 and Figure 11 show the settlement of the berm (DV2) to evaluate the reinforcement effectiveness. The unreinforced portion collapsed at 220gal, while the reinforced portion with three sheets of geogrid collapsed at 355gal. The test results shows that the reinforcement with geogrids was effective in preventing settlement. The reinforcement effectiveness with three sheets

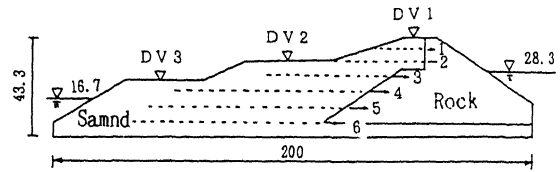


Figure 10. Small scale shaking table test model reinforced with geogrids

Table 3. Case of the shaking table test reinforced with geogrids

Case	Small scale model				Large scale
	1	2	3	4	5
Reinforced part	0	1~3	1~4	1~6	4
	In Fig.10				In Fig.12

Table 4. Properties of geogrid

mesh size (mm)	strength (kg/m)	open area ratio(%)
6 x 6	530	62

Table 5. Test results in the small scale shaking table test

Case	Reinforced part (In Fig.10)	Settlement at DV2		
		220gal	355	460
1	0	62	—	—
2	1, 2, 3	42	64	—
3	1, 2, 3, 4	0.1	10	21
4	1, 2, 3, 4, 5, 6	0.4	10	21

is appreciable, but four sheets of geogrid is more effective. The test results of Cases 3 and 4 with 460gal show that there is no difference in the effectiveness with four and six sheets of geogrid. The fourth sheet of geogrid was located between the saturated and unsaturated zones of the embankment. The tests indicate that the reinforcing effect of geogrids in the saturated zone is small.

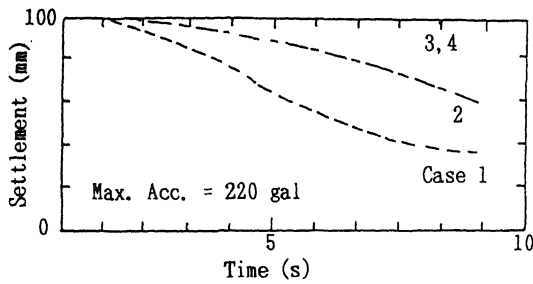


Figure 11. Settlement at berm (DV2)

### 3.2 Large scale shaking table test

In the large scale shaking table test, the effectiveness of embankment reinforcement with geogrids was investigated with a model where the ground and embankment were made with loose sand. The model was made like the small scale model, and a plan of the large scale model is shown in Figure 12. The input sine wave had a frequency of 3Hz, and the input acceleration was increased in stages, 220, 350, and 450gal. The resonance frequency of the model was around 24Hz.

The relative density of the dam and foundation,  $D_r$ , was 50%. Figure 13 shows the settlement of the crest (DV1). With reinforcement, settlement is reduced to 40% of the unreinforced test results in 2.2b. The deformation was even, and there were fewer cracks than without reinforcement.

The results of the large and small scale model tests show that reinforcement with geogrids prevents settlement (deformation) of the embankment.

## 4. Analysis of the shaking table tests

The effectiveness of reinforcement with continuous fibers was confirmed by the shaking table tests, and the following is an analysis of the effectiveness by simulation of the large shaking table test. The dynamic analysis program "DIANA - J2" was used.

### 4.1 Method of analysis

The constitutive law used in the analysis is the Densification model. The model uses Endochronick equation for the increase of pore water pressures. Assuming a total strain,  $\epsilon$ , given by the sum of the effective strain,  $\epsilon'$ , and the autogenous volumetric strain  $\epsilon_v$ . The autogenous volumetric strain is defined by the following equation by use of the empirical parameters A and B, and the damage parameter  $\kappa$ .

A plane strain model divided into 280 elements was used in the analysis (Figure 14).

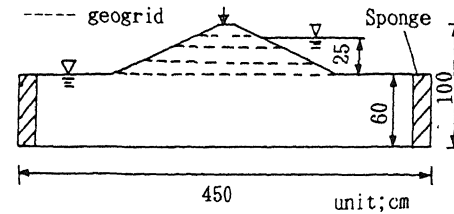


Figure 12. Large scale shaking table test model reinforced with geogrids

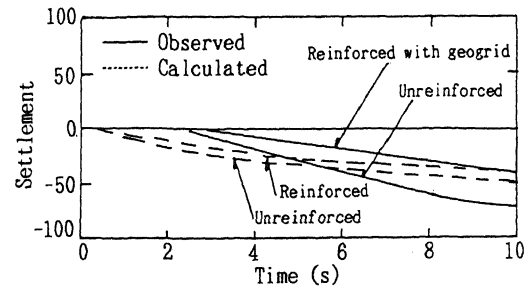


Figure 13. Comparison between the observed and calculated settlements at crest (DV1)

$$\text{Total strain } \epsilon = \epsilon' + \epsilon_v$$

Autogenous volumetric strain

$$\epsilon_v = \frac{A}{B} \ln(1+B\kappa)$$

Table 6 shows values used in the analysis and the parameters of the Densification model.

### 4.2 Analytical results

The shaking table test at the maximum input acceleration of 250gal were compared with the analytical results. Figure 15 shows the time history of pore water pressures in the unreinforced test and in the analysis in each part for a) lower body (P1), b) foundation center (P2), and c) lower foundation (P3). The time till pore water pressure increases agrees well until the initial stage of liquefaction.

The pore water pressures in both cases increase to the effective overburden pressures, while the calculated values increase earlier than the test values. Figure 13 shows the settlement of the crest. After a 10-second loading, the test shows a settlement of about 70mm in unreinforced case, and this is reduced 60% to about 40mm in reinforced case. This verifies the effectiveness of reinforcement with continuous fibers. The analysis shows the settlement in unreinforced case reduced by about 85% in reinforced case. Here the rein-

Table 6. Material parameters for the analysis

Parameter	Found.	Embank.	Reinforced part
$\phi$	37.6	37.6	43.4
$C$ (kgff/cm <sup>2</sup> )	0.03	0.03	1.08
Endo-choronic parameter	$\gamma$	3.0	3.0
	A	0.103	0.039
	B	74.5	34.3
Poisson's ratio $\nu =$		0.35	

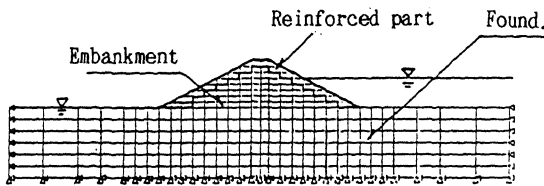


Figure 14. Finite element model for the analysis

forcement due to continuous fibers is qualitatively confirmed. The effectiveness may depend on the restraint from the top, with an increase in apparent cohesion of the part reinforced with continuous fibers (deformation mode after loading in Figure 16). In the analysis, the lower body foundations were almost completely liquefied. The main deformation occurred with in 4 seconds of loading. In the tests, the deformation continued after liquefaction of the ground, but this was not the case in the analysis.

### 5. Conclusions

To investigate the effectiveness of reinforcement against earthquakes with continuous fibers or geogrids in earth structures where embankments of foundations and embankments are subject to liquefaction, shaking table tests with small and large scale models were performed.

Embankment structures reinforced with continuous fibers showed qualitatively adequate effectiveness. The effectiveness was also appreciable in structures reinforced with geogrids where embankment or foundations plus embankment were prone to liquefaction. It is considered that reinforcement with geogrids, if applied in unsaturated sectors, is very efficient.

A theoretical analysis of the shaking table

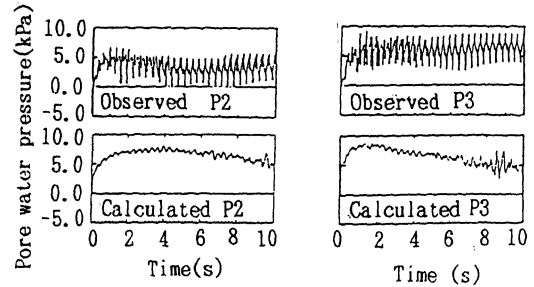


Figure 15. Observed and calculated excess pore water pressure P2 in the unreinforced model tests

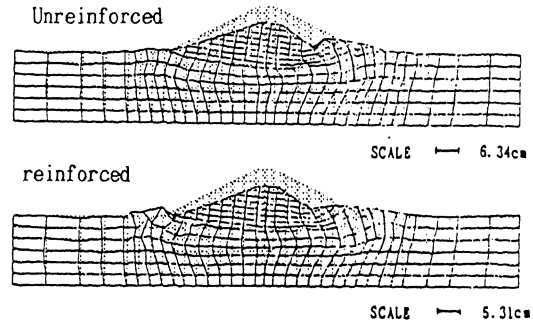


Figure 16. Calculated deformation mode after loading

tests qualitatively confirmed the effectiveness of continuous fibers with the Densification model, up to the initial stage of liquefaction. However, the final amount of deformation does not agree well with the test results. Further investigation including more parameters will be required.

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