Reinforcement effects of high strength geosynthetic to embankment on liquefied ground

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ABSTRACT: Countermeasures such as an increase in soil density, dissipation of pore water pressures leading to increased solidifaction and reductions in the level of the water table are commonly used techniques when embankments are constructed over ground which is subjected to liquefaction. On the other hand, it is effective to develop the economical reinforcing technique that can restrain the deformation of soil structure within allowable range. In this study degrees of deformation are examined when basal mattresses using high strength geosynthetic reinforcement are used on artificial ground which is subjected to liquefaction. And its behavior was simulated by 2-D FEM called ALID. Moreover, effect of reinforce due to high strength geosynthetic was evaluated under the various conditions. As a result, several conditions that the geosynthetic works efficiently to limit deformation of embankment on liquefied ground were pointed out.

1 INTRODUCTION

When embankments are constructed on liquefiable soil, liquefaction remediation such as increasing soil density, dissipating pore water pressure, permeable grouting and lowering the groundwater level are usually taken. These measures, however, are major factors contributing to an increase in construction cost. It is believed, therefore, that a substantial cost reduction can be achieved if embankment deformation in the event of liquefaction can be kept within an allowable range by reinforcing the bottom zone of the embankment without taking measures to control the underlying liquefiable ground.

As the first step in this study, a full-scale model experiment was conducted. In the experiment, an embankment reinforced with a basal mattress consisting of high-strength geosynthetic reinforcing elements, mattress frames and crushed stone used as mattress fill was constructed on the surface of ground to be artificially liquefied by use of control blasting. The flow accompanying liquefaction and the settlement accompanying the dissipation of pore water pressure observed in the experiment were simulated by using the 2-D liquefaction flow analysis program ALID(Analysis for Liquefaction-Induced Deformation) and the embankment reinforcing effect of the high-strength geosynthetics was investigated. In this study, the conditions under which high-strength geosynthetic mattresses contribute to reinforcement were identified by using a model capable of simulating experimental results.

2 ARTIFICIAL LIQUEFACTION EXPERIMENT

2.1 *High-strength geosynthetic:Nagao et al.(1999) (Paralink 200L)*

The high-strength geosynthetics used are planar reinforcement structures formed mainly by composite strips consisting of dense bundles of continuous polyester fibers encased in polyethylene sheaths. The strips are equally spaced to form a 4.5-meter-wide planar structure at interval of 0.18m.

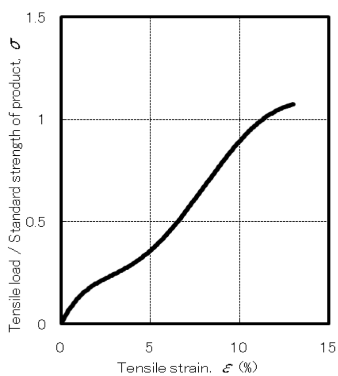

Figure 1. Tensile properties of high-strength geosynthetic

Figure 1 shows the tensile properties of the high-strength geosynthetic elements. As shown, the breaking strain is about 13%, and the strain under the load corresponding to the standard strength of the geosynthetic product is about 11%.

2.2 Experimental method

Figure 2 shows the 50 cm thick high-strength geosynthetic mattress constructed for the experiment. The embankment on the mattress was constructed with sand with low percentages of fines obtained by dredging. The embankment has a height of 3 m, a crest width of 3 m and a slope of 1:2.0 (vertical : horizontal). Explosives used for artificial liquefaction in the experiment were water gel type emulsion explosives, which characterizations are about 6,000m/sec of detonation velocity and high quality of water resistance. The plumb boreholes to install explosives were driven with the interval of 6.5m. The explosives of 2kg and 4kg in weight were set at GL-4.0m and GL-8.0m in each depth. Strains in the high-strength geosynthetic reinforcement in the transverse direction of the embankment were measured at two locations at the upper surface of the mattress and five locations at the lower surface of the mattress. At each strain measurement location, a strain gauge was installed on the upper surface and underside of the high-strength geosynthetic reinforcement. Strain gauges capable of measuring strains of up to 20%. The settlement and horizontal displacement of the embankment were measured by surveying stakes used as markers.

Figure 2. Mattress construction

2.3 Experimental results:Konami et al.(2008)

Figure 3 shows the time series of pore water pressure at the depth of 4 m at the center of the embankment in the reinforced embankment section. Because pore water pressure is greater than 90% of the effective overburden pressure of 99 kPa including the embankment load, it can be inferred that the soil was almost completely liquefied at this location. In contrast, the pore water pressure at the depth of 8 m was only about 30% of the effective overburden pressure, and no marked increase in pore water pressure was observed. These results of pore water pressure observation indicate that liquefaction occurred above the lower boundary of layer As3 as shown in Figure 4. In layers As4 and As5, no significant increase in pore water pressure was observed, indicating that liquefaction did not occur in these layers.
Deformation of ground and embankment and tension in reinforcement will be describe with results of analysis.

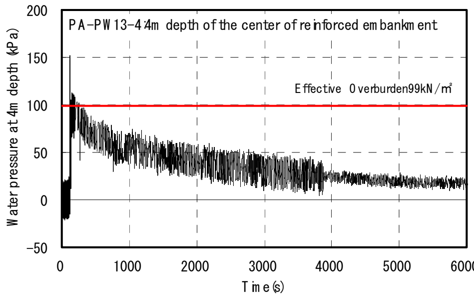

Figure 3. Pore water pressure in the soil

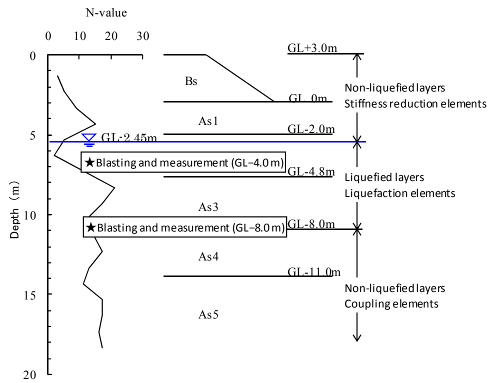

Figure 4. SPT N-value and geological profile

3 FINITE ELEMENT ANALYSIS

3.1 Simulation of experiment:Ohwada et al.(2008)

a) Simulation model

The liquefaction-induced flow observed in the experiment and the settlement due to the dissipation of pore water pressure were simulated by using the 2-D liquefaction analysis program ALID:ALID Research Society(2007) and a study was made on the modeling of the soil reinforced with the high-strength geosynthetic. Figure 5 shows the analyzed cross section. In the analysis, which was performed under the conditions shown in Tables 1 and 2, case studies were conducted by parameterizing the design horizontal seismic coefficient for the calculation of the liquefaction resistance factor and the stiffness reduction ratios of the non-liquefied layers and the embankment. The parameter ranges are 0.15 to 0.25 (Type I) and 1 to 1/100, respectively. The stiffness reduction ratios G_l/G_N of the non-liquefied layers and the em

Table 1. Analytical constants

Soil layer	Type of element	Deformation characteristics	Shear modulus G_N kN/m^2	Poisson's ratio ν	Wet unit weight γ kN/m^2	Liquefaction resistance factor FL	Fine particle content F_c%	Relative density D_r%
Bs	SOLID	Stiffness reduction	4000	0.33	15.6	–	–	–
As1	SOLID	Stiffness reduction	12000	0.33	16.1	–	–	–
As2	SOLID	Stiffness reduction	5000	0.33	17.2	–	–	–
As2	SOLID	Elastic liquefaction	2000	0.33	17.5	Table 2	19.0	23.0
As3	SOLID	Elastic liquefaction	17000	0.33	17.7	Table 2	7.7	62.5
As4	SOLID	Coupling elemants	16000	0.33	17.6	–	–	–
As5	SOLID	Coupling elemants	16000	0.33	16.8	–	–	–

Table 2. FL values

Liquefied layers	K_h=0.15		K_h=0.20		K_h=0.25	
	Non-Embakment section	Embakment section	Non-Embakment section	Embakment section	Non-Embakment section	Embakment section
As2	0.64	0.74	0.48	0.56	0.38	0.45
As3	1.27	1.56	0.96	1.17	0.76	0.93

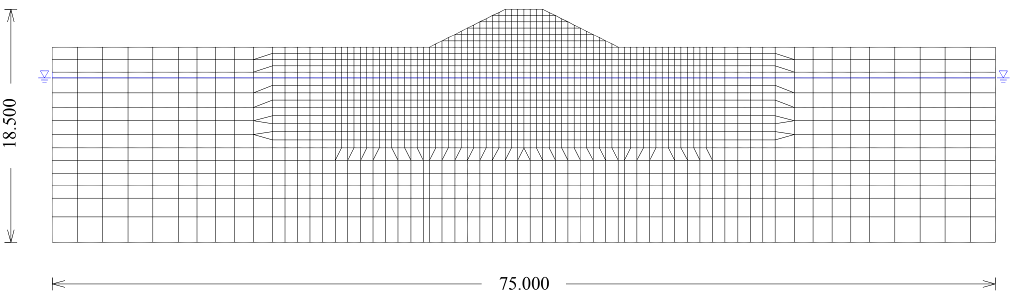

Figure 5. Analysis model

bankment were lowered from the initial stiffness G_N at a uniform rate. To identify liquefied elements, the stiffness reduction ratio due to liquefaction was estimated from the relationship between the fine particle content and the liquefaction resistance factor proposed by Yasuda et al.(1999), and volume compressibility was estimated from the relationship between relative density and the liquefaction resistance factor proposed by Ishihara et al(1992). The non-liquefied layers and the embankment above the liquefied layers were expressed as stiffness-reducing elements.

b) Non-reinforced embankment simulation results

Main tendencies revealed by the simulation analysis are as follows:

- Settlement increases as the design horizontal seismic coefficient becomes greater (Figure 6).
- Toe-of-slope horizontal displacement was little affected by the design horizontal seismic coefficient; instead, it was affected predominantly by the stiffness reduction ratio of the non-liquefied layers (Figure 7).

The optimum value of the stiffness reduction ratio of the non-liquefied layers estimated from through comparison with measured values is, from the viewpoint of toe-of-slope horizontal displacement, about 1/10 (Figure 7).

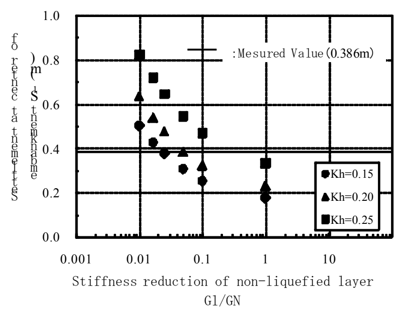

Figure 6. Relationship between the stiffness reduction ratio and center-of-embankment settlement

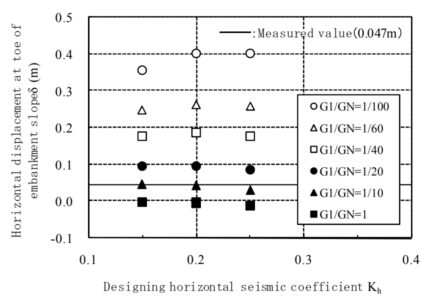

Figure 7. Relationship between the design horizontal seismic coefficient and toe-of-slope horizontal displacement

The optimum value of the design horizontal seismic coefficient is, from the viewpoint of the amounts of settlement shown in Figures 6, is about 0.20 to 0.25 if the stiffness reduction ratio of the non-liquefied layers is 1/10.

c) Reinforced embankment simulation analysis results

The conditions for the reinforced embankment simulation analysis concerning ground structure, boundary conditions, treatment of liquefaction and non-liquefied layers and the extent of liquefied layers are the same as the conditions for the non-reinforced embankment simulation analysis. On the basis of the analysis results for the non-reinforced embankment, the design horizontal seismic coefficient and the stiffness reduction ratio of the non-liquefied layers were set at 0.22 and 1/10, respectively. A total of two analytical cases were defined depending on the presence or absence of reinforcement.

The reinforcement structure assumed in the analysis consists of two 0.5-meter-thick layers (one layer placed on top of the other) of crushed stone, each of which is wrapped in high-strength geosynthetic (1.4-mm-thick geogrid). In the analysis, this reinforcement structure was modeled as an integral beam element, and the axial stiffness of the beam element was determined solely according to the geosynthetic specifications shown in Table 3. Joints elements were not taken into consideration, assuming that sufficient friction can be obtained between the geosynthetic and the soil.

Table 3. Analytical constants for reinforcement

Element type	Modulus of elasticity E kN/m^2	Cross section area A m^2	Geometrical moment of inertia
BEAM	1300000	0.0028	1.7E-03

Table 4. Comparison between calculated values and measured values

Index of displacement		Settlement at center of embankment S_1	Settlement at toe-of-slope S_2 m	Horizontal displacement at toe-of-slope
Calculated	Non-reinfoced	0.379	0.187	0.039
	Reinforced	0.372	0.189	0.030
	Retio	0.98	1.01	0.77
Measured	Non-reinfoced	0.385	0.150	0.047
	Reinforced	0.390	0.160	0.028
	Retio	1.01	1.07	0.59

As shown in Table 4, the calculated values show fair agreement with the measured values. The ratio of the displacement in the reinforced soil case to the displacement in the non-reinforced soil case (displacement in reinforcement case /displacement in no reinforcement case) was calculated as an indicator of the reinforcing effect. The ratios thus obtained reveal that although neither the calculated value nor the measured value of embankment and toe-of-slope settlement indicates the effect of the reinforcement, both the calculated value (0.77) and the measured value (0.59) of toe-of-slope horizontal displacement do indicate the effectiveness of the reinforcement in reducing displacement. Also, as shown in Figure 8, the calculated value (11.1 kN/m) and the measured value (14.6 kN/m) of tension occurring in the reinforcing elements show fair agreement.

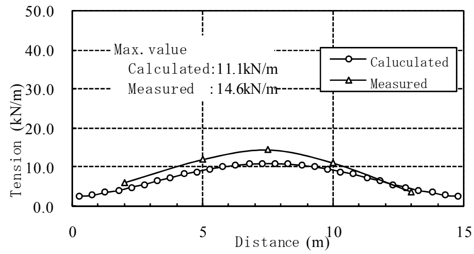

Figure 8. Tension distribution in reinforcement

3.2 Reinforcing effect of geosynthetic

In order to identify conditions that make the geosynthetic reinforcement effective in reducing displacement, a parameter study was conducted. The parameters studied were groundwater level, embankment height and the modulus of elasticity of the geosynthetic reinforcement. In all cases of analysis, it was assumed that the region below the groundwater level is the liquefaction zone (layer).

For the purposes of this study, the reinforcing effect is evaluated in terms of the amount of reduction in horizontal displacement. Major tendencies indicated by the analytical results shown in Figures 9 to 16 are as follows:

· As the groundwater level rises, toe-of-slope horizontal displacement of the embankment tends to increase and the reinforcing effect (= δ in reinforcement case/δ in no reinforcement case) tends to increase.

· As the stiffness of the geosynthetic reinforcement increases, toe-of-slope horizontal displacement of the embankment tends to decrease and the reinforcing effect tends to increase.

· As embankment height increases, toe-of-slope horizontal displacement of the embankment tends to increase and the reinforcing effect tends to decrease.

Figure 17 shows distributions of horizontal displacement (directly under toe of embankment slope) in the ground. As shown, the deformation of the embankment was reduced by the geosynthetic reinforcement, and, as a consequence, deformation due to lateral flow in the ground was also reduced.

The study results indicate that although the geosynthetic reinforcement seems to have little effect on settlement, it is highly effective against horizontal displacement in the cases in which the groundwater level is high and close to the ground surface.

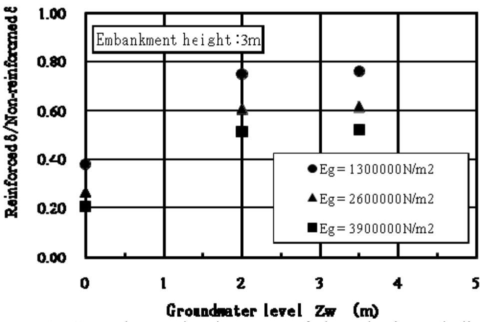

Figure 9. Groundwater level vs. toe-of-slope horizontal displacement (H=3 m)

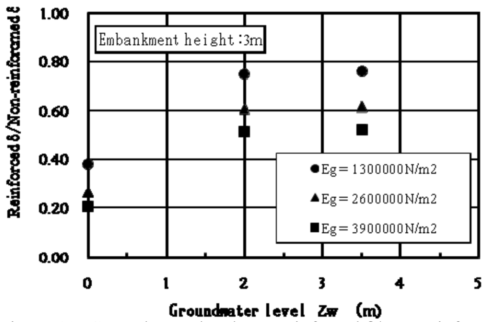

Figure 10. Groundwater level vs. Reinforced δ/Non-reinforced δ (H=3 m)

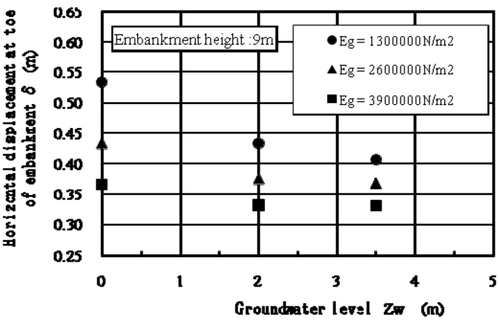

Figure 11. Groundwater level vs. toe-of-slope horizontal displacement (H = 9 m)

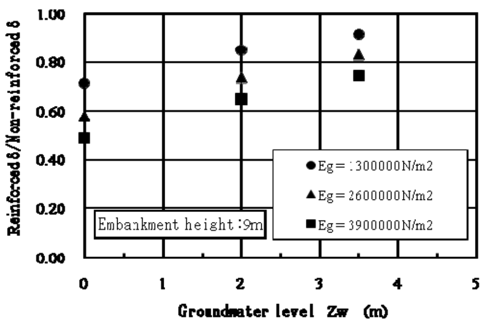

Figure 12. Groundwater level vs. Reinforced δ/Non-reinforced δ (H=9 m)

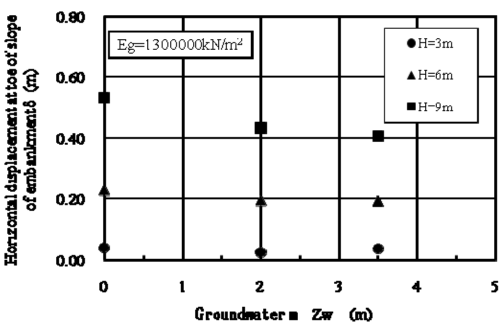

Figure 13. Groundwater level vs. toe-of-slope horizontal displacement (E_g=1300000kN/㎡)

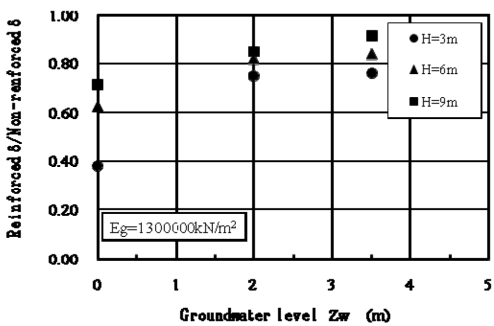

Figure 14. Groundwater level vs. Reinforced δ/Non-reinforced δ (E_g=1300000kN/㎡)

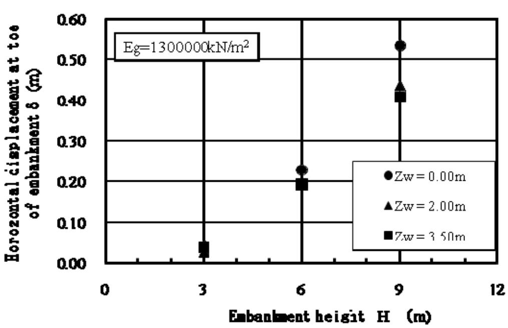

Figure 15. Embankment height vs. toe-of-slope horizontal displacement

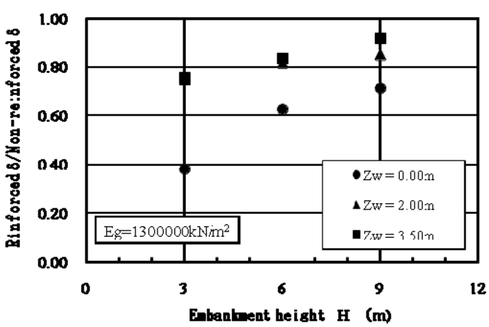

Figure 16. Embankment height vs. Reinforced δ/Non-reinforced δ (E_g=1300000kN/㎡)

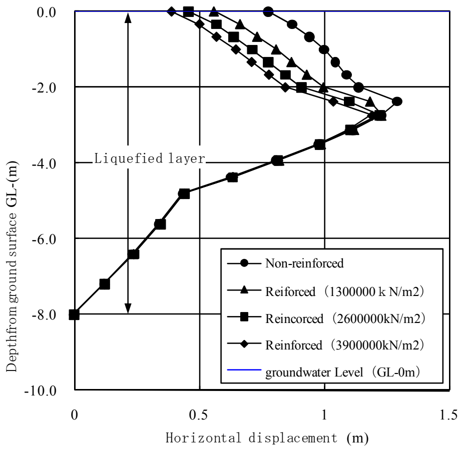

Figure 17. Horizontal displacement distribution in the ground

The study results also indicate that the reinforcing effect of the geosynthetic reinforcement can be further increased by increasing its modulus of elasticity. The fact that as the height of the embankment increased, the reinforcing effect decreased suggests that in the case of a high embankment, geosynthetic mattresses with high stiffness will be effective.

4 CONCLUSION

The results obtained in the experiment suggest that liquefaction-induced horizontal displacement of an embankment can be reduced by reinforcing the basal region of the embankment with geosynthetics. A simulation analysis of liquefaction experiments was performed on the basis of observation results, and the following conclusions have been drawn:

・ In the experiment, it was possible to simulate the behavior of the embankment with high accuracy by setting the design horizontal seismic coefficient at 0.20 to 0.25 and the shear stiffness reduction ratio at 1/10 of the initial stiffness.

・ Toe-of-slope horizontal displacement δ is heavily dependent on the shear stiffness reduction ratios of the non-liquefied layers and the embankment. In the simulation analysis, high accuracy of simulation was achieved by setting the stiffness reduction ratio for the non-liquefied layers and the embankment at about 1/10 of the initial stiffness.

・ It has been shown that the effect of the high-strength geosynthetic reinforcement in reducing the horizontal displacement of the embankment can be simulated by modeling the geosynthetic with a beam element.

A parameter study was conducted to identify conditions that enhance the reinforcing effect of the geosynthetic. The study led to the following findings:

・ Higher reinforcing effects were achieved in the cases where the groundwater level is close to the ground surface.

・ The reinforcing effect was enhanced by increasing the modulus of elasticity of the geosynthetic.

Thus, the simulation analysis based on the experiment results led to the identification of a number of conditions that make geosynthetic reinforcement very effective.

As the next step, it is necessary to verify the reinforcing effect of geosynthetics through model experiments or by other means and establish a method for quantitative evaluation of the reinforcing effect at the design stage.

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