Effect of lattice-frame reinforced geosynthetics on seismic stability improvement of embankment on loose sand deposit

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ABSTRACT

The authors have developed a specific geosynthetic for reduction of differential settlement, composed of woven textile sheet and lattice frame of mortar-injected fabric hoses, providing high bending rigidity. To examine the reinforcement effect of this geosynthetic system, called the lattice-frame reinforced (LFR) sheet, a series of dynamic centrifugal model tests and finite element analyses were carried out. The results showed that the LFR sheet was capable of reducing differential settlement due to seismic liquefaction and effective to reduce horizontal deformation of liquefiable layer as well as the case in which the improved zone was totally set under the embankment.

Keywords: liquefaction, differential settlement, geosynthetics, centrifuge, finite element analysis

1 INTRODUCTION

The authors have developed a specific geosynthetic for reduction of differential settlement, composed of a woven textile sheet and lattice frame of mortar-injected fabric hoses providing high bending rigidity (Fig. 1). This geosynthetic system, referred to as a lattice-frame reinforced (LFR) sheet, is mainly applied for surface soil stabilization, as described in Table 1.

The LFR sheet is capable of mitigating the damage from differential settlement through its high bending rigidity. The LFR sheet could thus reduce the differential settlement caused by liquefaction due to earthquakes.

To examine the reinforcement effect of the LFR sheet, a series of dynamic centrifugal model tests were carried out. Moreover, to confirm the centrifugal test results, numerical finite element analyses were conducted.

2 CENTRIFUGAL MODEL TESTS 5)

2.1 Test program

Centrifuge tests were performed on four models equipped with different countermeasures as well as a benchmark model with no countermeasures. The model configurations are illustrated in Fig. 2 at the prototype scale. Case 1 is the benchmark model for which a 2.8 m high embankment was constructed on loose sand deposit having a thickness of 6.5 m. In Cases 2 and 3, the

| Case | Purpose |
|------|---------|
| 1    | Land-filling on extremely soft ground Reduction of differential settlement 1) |
| 2    | Temporal road construction on soft ground Subgrade stabilization 2,3) |
| 3    | Temporal rail-track construction on soft ground Subgrade stabilization |
| 4    | Temporal site-preparation for mobile crane work on soft ground Soil stabilization 4) |

Table 1. Typical applications of the LFR sheet.

Fig. 1. Basic features of the LFR sheet.

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loose sand deposit was densified by gravel compaction piles (GCPs). However, in Case 3, the densified area was restricted to the vicinity of the embankment toe. In Cases 4 and 5, the LFR sheet was placed beneath the embankment to improve the seismic stability. Case 5 is similar to Case 3 in all aspects except for reinforcement with the LFR sheet.

2.2 Model preparation and testing procedure

The model for the loose sand deposit was prepared by the air pluviation method with 55% relative density using dry Toyoura sand. During the pluviation process, the pore mass ratio and pluviation height were held constant to achieve a uniform sand deposit. After the pluviation, the model ground was slowly saturated by infiltrating silicone oil from the bottom until the pore fluid came up to the ground surface. The viscosity of this oil was 50 times that of water. The embankment was built using a mixture of kaolin clay and Toyoura sand (1:10 weight ratio) with a water content of 18%. To maintain the uniformity of the model sandy ground, model embankment was compacted to 92% of the standard Proctor ratio in another container and frozen in a freezer. After the model embankment was completely frozen, it was gently placed on the model ground and was left on the centrifuge platform for at least 10 hours to defrost at the test room temperature. The densified area tested in Case 2, 3 and 5 was prepared by the air pluviation method with 93% of relative density using a mixture of Toyoura sand and silica sand (9:1 weight ratio).

The materials used for the model of the LFR sheet were selected so as to be consistent with the similarity law for the tensile rigidity of the sheet and the bending rigidity of the lattice frame as summarized in Table 2. In past applications of the LFR sheet, lattice size was determined according to each requirement. This study employed a lattice size of 3.0 m × 2.5 m as shown in Fig. 3.

Figure 4 is an example of the test model. A rigid model container with inner dimensions of 700 mm in length, 200 mm in width, and 185 mm in height was used. For reduction of the horizontal displacement constraint, silicone dampers were placed on both sides of the model ground. To observe seismic deformation of the embankment constructed on loose saturated sand deposit, dynamic shaking table tests were performed under 50 g of centrifugal acceleration. A time history of the horizontal shaking wave input to the base of the models is indicated in Fig. 5. Each model was shaken two times in succession with sinusoidal waves of 3.0Hz prototype frequency for approximately 17 seconds. Peak acceleration of the shaking wave was 200 gal. After the dissipation of excess pore water pressure caused by the first shaking event, each model was subjected to the second shaking.

![Fig. 2. Configurations of centrifugal models.](image)

**Table 2. Features of the model LFR sheet.**

| Part          | Specification | Centrifugal model | Actual product      |
|---------------|---------------|-------------------|---------------------|
| Woven textile sheet | Material: Polypropylene film | Centrifugal model: 0.0075 (0.38") mm | Actual product: Polyester textile |
| Thickness     | 0.015 (0.76") mm | 0.015 (0.76") MN/m | 0.38 mm |
| Tensile rigidity | 0.0075 (0.38") mm | 0.015 (0.76") MN/m | 0.51 MN/m |
| Lattice frame | Material: P.T.F.E. round bar | Centrifugal model: 2 (100") mm | Actual product: Mortar + fabric hoses |
| Diameter      | 533 N/mm² | 100 mm | 600 N/mm² |
| Elastic modulus | 4.19E-7(2.62") kN · m² | 100 mm | 3.13 kN · m² |
| Bending rigidity | 4.19E-7(2.62") kN · m² | 100 mm | 3.13 kN · m² |

*Prototype scale under 50g of centrifugal acceleration

![Fig. 3. The LFR sheet used in this study.](image)
2.3 Test results

*Acceleration and excess pore water pressure*

Figure 6 shows the time histories of acceleration (ACC) and excess pore water pressure (EPP) observed during the first shaking event in Cases 2, 4 and 5. In Fig. 6, $\sigma_{vo}$ is the initial vertical effective stress including embankment overburden.

In the free field, the excess pore water pressure resulted in liquefaction. Accordingly, the acceleration gradually disappeared due to the reduction in soil stiffness and strength associated with liquefaction.

In Cases 2 and 5 in which the foundation ground was densified, it was found that pore water pressure generation was suppressed below the slope toe, compared with Case 4. At the surface of this area, the asymmetric response pattern showed large spikes during each cycle of excitation (Cases 2 and 5). This was considered to be associated with the tendency of the soil skeleton to dilate at large strains, as reported by Adarier et al. (1998)\(^6\).
**Ground deformation**

Figure 7 shows the permanent deformation observed in each model after the second shaking event.

**Case 1: Benchmark**

The foundation ground showed a large horizontal displacement associated with the liquefaction that occurred in the free field. Then, the bottom of the embankment stretched toward the free field and many cracks were generated from the bottom to the surface as well as in the reverse direction.

**Case 2: Total densification**

After two shaking events, the foundation ground showed slight settlement and remained approximately level. However, many cracks were observed in the embankment. As shown in Fig. 6, the recorded accelerations in this case were larger than in the other cases. Based on this result, it was inferred that larger acceleration propagated to the embankment due to the high stiffness of the densified foundation, resulting in the generation of many cracks.

**Case 3: Partial densification**

Lateral deformation of the foundation ground was suppressed by the densification area set beneath the slope toe. Despite this, many cracks were found in the embankment, as with Case 2. It should be noted that two major cracks starting from points adjacent to the inside boundary of the densified area propagated vertically throughout the embankment body.

**Case 4: The LFR sheet**

The embankment showed uniform settlement with the initial shape mostly retained and differential settlement of the foundation ground to a small extent. Thus, crack propagation from the bottom of the embankment was not observed in this case. Cracks were mainly observed in the vicinity of the embankment surface.

**Case 5: The LFR sheet and partial densification**

In contrast to Case 3, no distinctive major cracks were observed. The lateral deformation in this case was smaller than that of Case 3 due to the tensile resistance of the LFR sheet.

| CASE | Photo | Sketch (---:crack, ---:trace of the markers) |
|------|-------|---------------------------------------------|
| 1    | ![Image](1.png) | ![Sketch](1 Sketch.png) |
| 2    | ![Image](2.png) | ![Sketch](2 Sketch.png) |
| 3    | ![Image](3.png) | ![Sketch](3 Sketch.png) |
| 4    | ![Image](4.png) | ![Sketch](4 Sketch.png) |
| 5    | ![Image](5.png) | ![Sketch](5 Sketch.png) |

Fig. 7. Sketches of mapped deformation (After the second shaking event).
Consideration of experimental observations

Figure 8 indicates the depth distribution of the lateral displacement of the foundation ground below the slope toe and at the slope top. In the benchmark model (Case 1), a relatively large displacement was observed around a depth of 4.5 m (near the top of slope) or 3.5 m (slope toe). These were inferred to be slip lines related to a wedge of local failure that was occurred in the underlying layer below the center of the embankment. Based on a comparison between Case 1 and Case 4, lateral displacement prevailed in the shallow area in Case 4. In Case 4, in which the LFR sheet was installed beneath the embankment, it can be assumed that the embankment overburden was uniformly distributed by the load dispersion effect of the sheet and that local failure of the underlying layer was prevented. Therefore, the deformation of the foundation beneath the embankment was predominately one-dimensional compression and lateral deformation was restricted to the superficial zone. The same tendency was also confirmed in a comparison between Case 3 and Case 5. Also, it should be said that the lateral displacement observed in Case 5 was almost equivalent with that of Case 2. The total densification employed in Case 2 obviously imposes on the reinforcement works to pay the largest efforts and approximately the same reinforcement effect is able to be achieved in smaller efforts by using the LFR sheet.

As shown in Fig. 7, crack generation from the bottom of the embankment was not observed in the tests using the LFR sheet (Case 4 and 5). It is considered that the LFR sheet suppressed differential settlement and provided tensile resistance, and then the horizontal stretching of the embankment bottom prevailed consequently. Crack generation is apparently relevant to the stability problem and the LFR sheet is thought to be effective in improvement of seismic stability of the embankment.

3 NUMERICAL ANALYSES

3.1 Procedures

To confirm the seismic reinforcement effect of the LFR sheet observed in dynamic centrifugal model tests, a series of numerical analyses was implemented by using the FLIP 2-dimensional FEM analysis program in which the cyclic mobility model (2) supposed by Lai et al. (1992) was employed to evaluate the response of a liquefiable layer under seismic conditions. The FE mesh is shown in Fig. 9 based on the centrifuge prototype mentioned above. Bottom boundary is fixed, and the viscous boundary condition is given for lateral boundary considering the damper in experiment.

Table 3 summarizes the soil parameters used in this simulation. Almost parameters can be defined by the conventional method (1), which requires the physical and liquefaction properties of soil. Some of parameters, $S_{us}$ representing maximum shear stress under undrained condition and cohesion because of its unsaturated condition in centrifugal tests, are determined parametrically as the result of simulations.

The FE model for the LFR sheet consists of two components. One is the elastic material elements that are set at equal intervals along the direction parallel to Fig. 9. These represent the jackets set along the direction orthogonal to the shaking direction described in Fig. 3 (hereafter the “orthogonal jackets”). The material properties of the orthogonal jackets are given the same values, as summarized in Table 2. Another component is the elastic trussed beam elements set between the orthogonal jackets representing the sheet and the jackets set along the direction parallel to the shaking direction (hereafter the “parallel jackets”).

![Figure 8](image-url)  
Fig. 8. Distributions of lateral displacement observed in the foundation ground.

![Figure 9](image-url)  
Fig. 9. Finite element mesh used in this study.

Table 3. Soil parameters for finite element analyses.

| Parameters | Embankment | Foundation | Notes |
|------------|------------|------------|-------|
| $\rho_{sat}$ | 18.1kN/m$^3$ | 18.8kN/m$^3$ | Physical properties |
| $n$ | 0.407 | 0.437 | |
| $C_{und}$ | 56.4MN/m$^2$ | 37.5MN/m$^2$ | Deformation characteristics |
| $mG$, mK | 0.5 | 0.5 | |
| c | 20kN/m$^2$ | 0.0 kN/m$^2$ | |
| $\phi_r$ | 39.7 | 36.2 | |
| $h_{max}$ | 0.24 | 0.24 | |
| $S_{us}$ | - | 34.0kN/m$^2$ | Liquefaction characteristics |
| $f$ | - | 28.0 | |
| $\omega$ | - | 1.70 | |
| $p_1$ | - | 0.60 | |
| $p_2$ | - | 1.10 | |
| $c_1$ | - | 1.79 | |
| $s_1$ | - | 0.005 | |
The trussed beam elements were installed in an attempt to express the displacement confining effect and flexural capacity of the parallel jackets. Although the material properties for the trussed beam elements should be determined with regard to the planar reinforcement effect of the LFR sheet, the elastic modulus of the trussed beam elements is conventionally given as 10 times that of the material employed in the centrifuge model tests. Since lateral displacement of embankment is overestimated.

Liquefaction program FLIP solves the earthquake response of the liquefiable ground under quasi constant volume condition which is equivalent to undrained condition. Therefore, it cannot consider the dissipation of excess pore water pressure after earthquake and its induced ground settlement which is obviously measured in experiment. In order to consider this induced settlement in the simulation, it is post-estimated by the chart 9), which is the relation between volumetric strain due to liquefaction and maximum shear strain during liquefaction, suggested by Ishihara and Yoshimine (1992).

### 3.2 Results

The analyzed bottom shape of the embankment after the first shaking event is plotted in Fig. 10 based on normalized settlement. To examine the reduction effect on differential settlement, the plotted settlement is normalized by the settlement of underlying layer below the embankment center. In the benchmark test (Case 1), a relatively larger differential settlement is estimated compared to the test with the LFR sheet (Case 4).

Figure 11 indicates the computed distribution of the minimum principal shear strain (compression: positive) in the embankment just after the seismic motion. Similar deformation such as the cracks that pierced the embankment was found in the centrifugal tests without the LFR sheet. In the benchmark model, large deformed area showed zonal and vertical distribution throughout the embankment. This seems to be generated by the same mechanism that includes lateral stretching of the embankment bottom associated with differential settlement of the foundation ground. On the other hand, such cracks were not found in the centrifugal tests with the LFR sheet. Also, significant strain localization is not estimated in the analytical case with the LFR sheet. These results indicate the effectiveness of the LFR sheet on seismic reinforcement of earth structures.

### 4 CONCLUSION

To confirm the seismic reinforcement effect of the LFR sheet, a series of centrifugal model tests and numerical analyses were performed. In these examinations, the LFR sheet was installed beneath the embankment constructed on liquefiable loose sand deposit. The experimental and analytical results indicated the effectiveness of the sheet on seismic reinforcement. However, the procedure for determining the material properties given to the elements representing the components of the LFR sheet requires further research such as the comparative examination between the experimental and the analytical results.

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