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Effects of surface soil stabilization by a lattice-frame-reinforced sheet

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ABSTRACT: We developed a surface layer stabilization technique in which a sheet (e.g., woven geotextile, geogrid) is paved on a very soft ground and reinforced by a lattice-frame that consists of jackets (i.e., tubes made of woven textile) and mortar filled within the jackets. We performed an outdoor loading test using a lattice-frame-reinforced (LFR) sheet, and we confirmed that the differential settlement against a locally concentrated vertical load was much less than that without a lattice-frame. Further, we established a technique to estimate the settlement of the LFR sheet using a beam-on-elastic-foundation model.

1 INTRODUCTION

During earthwork projects in which the surface layer is stabilized by paving sheets (e.g., geotextile) on very soft ground, differential settlements are likely to occur because the sheet has a low bending resistance. In such a case, large tensile forces may break the sheet, which causes a rapid loss of soil. To increase the stiffness of the sheet, techniques such as partial solidification of the ground surface using cement, or installation of a lattice-frame made of bamboo stems together with the sheet, can be applied. However, these techniques have a high cost and require much additional time.

To resolve these problems, we have developed a new surface layer stabilization technique in which a sheet is paved on a very soft ground and reinforced with a lattice frame. To increase the bending stiffness of the sheet, the lattice frame has tubes made of woven textile, hereafter jackets, that are filled with mortar (Fig. 1; see also Kitamoto et al., 2003). The sheet may be made of fibernet, woven geotextile, or a similar material.

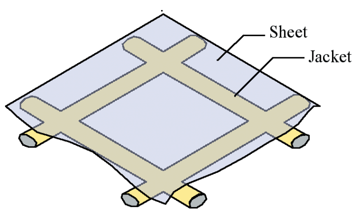

Figure 1. Basic features of the LFR sheet.

The jackets are made into a lattice pattern in the factory, so the only work remaining in the field involves spreading the sheet on the ground, as in a conventional sheet, and then pumping the mortar into the lattice-frame with high liquidity. Air in the jacket can easily flow out across the jacket surface while the mortar is being pumped.

2 SCHEME OF THE LOADING TEST

2.1 *Loading test for LFR sheet*

To evaluate the effects of the rigid lattice-frame, we conducted a real-scale loading test in the field (Fig. 2 & Photo 1; see also Yoshida et al., 2005). We prepared an artificial soft ground with a shear strength of about 1 kN/m^2 (Table 1) in a square area of dimension 10 m $\times$ 10 m. Then, we paved a sheet of size 12 m $\times$ 12 m, combined beforehand with jackets, to cover the ground. Jackets with a diameter of 10 cm were placed every 2 m beneath the sheet and tied with rope to the sheet at the crossing points (intersection of two jackets) and also at the midpoint between the crossing points. Then, we filled the jackets with mortar using a pump. In this case, the jackets were connected to each other at the crossing points so that the mortar flowing into a crossing point could diverge into three directions and quickly fill the entire lattice-frame. The diameter of the jacket at the crossing points was larger (15 cm) than that at other parts.

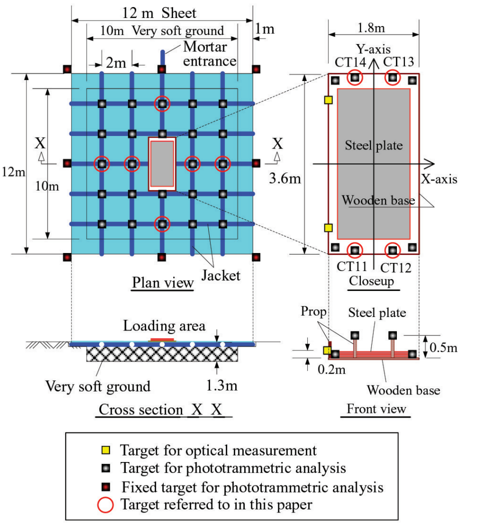

Figure 2. Arrangement of the loading test for the LFR sheet.

Photo 1. Panoramic view of the loading test for the LFR sheet.

Table 1. Properties of the artificial ground.

Density of soil particles	2.668 g/cm^3
Water content	63.5%
Gravel content (over 2 mm)	17.4%
Sand content (0.075 to 2 mm)	21.8%
Fine fraction content (under 0.075 mm)	60.8%
Maximum particle diameter	19 mm
Liquid limit	N.P.
Plastic limit	N.P.
Bulk density	1.60 t/m^3
Vane shear strength (Depth = 50 cm)	1 kN/m^2

After 48 hours of curing (i.e., after the mortar hardened), we ran a series of loading tests. Namely, we placed steel plates one-by-one on a wooden base (3.6 m × 1.8 m) at the center of the sheet, at intervals of 5 minutes. The size of a steel plate was 3 m × 1.5 m, and the thickness and the weight were 25 mm and 8.94 kN, respectively. The values of the accumulated vertical load and load strength at every loading stage are given in Table 2. The unconfined compressive strength of the mortar was 22 N/mm^2 at the time of the loading.

Table 2. Load applied at each stage.

Loading step (=# of steel plates)	Initial	Base	1	2	3	4	5	6	7	8	9	10
Total weight (kN)	0.00	1.62	10.56	19.51	28.45	37.39	46.34	55.28	64.22	73.17	82.11	91.05
Vertical load strength (kN/m^2)	0.00	0.25	1.63	3.01	4.39	5.77	7.15	8.53	9.91	11.29	12.67	14.05

Photogrammetric analysis was used to determine the behavior of the wooden base and the sheet surface, whereas optical measurements were used to trace the settlement of the wooden base. However, results from both methods were consistent, so we only describe the photogrammetric results here. At every loading stage, digital pictures for photogrammetric analysis were taken at two overhead positions two minutes after loading. According to the real-time optical measurements, the settling was significant at first, but after two minutes time, the settling had nearly stopped.

The specifications of the photogrammetric analysis are shown in Table 3. In this table, the resolutions are the value for arbitrary positions on a picture. At the targets set on the sheet and wooden base (Photo 2), the differences of altitude from the optical measurement were 10 mm or less.

Table 3. Specifications of the photogrammetric analysis.

Image size	4500 × 3000 pixels
Pixel size	8 µm
Focal length	14 mm
Baseline length	About 4 m
Object distance	About 9 m
Horizontal resolution	5 mm
Vertical resolution	12 mm

Photo 2. A target for the photogrammetric analysis.

2.2 *Loading test for a conventional sheet*

To compare properties of the LFR sheet to those of a conventional sheet, we also ran a loading test with a conventional sheet (fibernet), whose construction cost, including the material price was estimated to be almost equal to the cost of the LFR sheet. Table 4 shows the specifications of both sheets used for the loading tests.

Table 4. Sheet specifications for the loading tests.

	Conventional Sheet	LFR sheet	
		Sheet	Jacket
Form	Fibernet	Woven textile	Woven textile
Material	Polyester & Plastic	Polyester	Polyester
Tensile strength	70 kN/m	76.7 kN/m	714 kN/m
Max. tensile strain	25%	17%	20%

3 TEST RESULTS

Photos 3 and 4 are snapshots around the loaded parts at the final stages of loading of the conventional and LFR sheet, respectively. The base settlements (average of CT11 to CT14) during loading up to about 14 kN/m^2 are shown in Fig. 3. For the conventional sheet, the curve became steeper as the load increased and the 10th steel plate could not be placed because the wooden base did not stop settling after the 9th steel plate was placed. On the other hand, for the LFR

Photo 3. Conventional sheet at σ_v = 12.67 kN/m^2.

Photo 4. LFR sheet at σ_v = 14.05 kN/m^2.

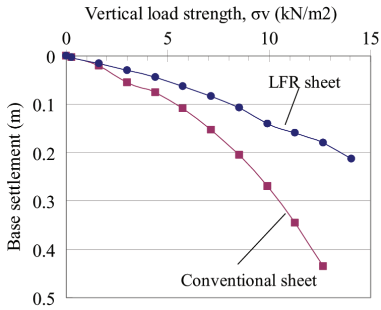

Figure 3. Settlement during the loading tests.

sheet, the slope of the curve in Fig. 3 is nearly uniform, and the settlements were about half or less than those of the conventional sheet throughout the test.

The vertical load at the 10th stage of loading (14.05 kN/m^2) was almost as large as the earth contact pressure of the super-swamp-type bulldozers. For the LFR sheet, the base settled about 6 cm just after the first steel plate was loaded because initially the jackets did not penetrate into the soft ground. This initial settlement is subtracted from the curve in Fig. 3.

The surface settlements of the sheets during the tests are shown in Fig. 4. The plots show that the differential settlement was significantly reduced in the LFR sheet by the load distribution effect of the rigid lattice-frame. Namely, both the settlement of the base and the upheaval around the base were smaller than that with the conventional sheet, although there was only one jacket across the base length (3.6 m).

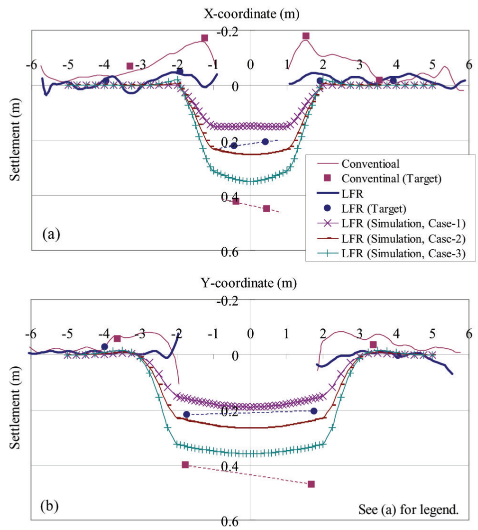

Figure 4. Accumulated settlement along the x-axis (a) and y-axis (b) at the final stage of loading (12.67 kN/m^2 for the conventional sheet and 14.05 kN/m^2 for the LFR sheet).

4 NUMERICAL ANALYSES

To better understand the behavior of the LFR sheet during earthworks under arbitrary conditions, we ran a series of numerical simulations of the final stage of the field loading (Shimada et al., 2005). The jackets were modeled as a beam-on-elastic-foundation along both the x-axis (y = 0 line) and the y-axis (x = 0 line) as shown in Fig. 5. The parameters used for the calculations are listed in Table 5. The bending stiffness of the jacket was evaluated using the actual bending test with mortar-filled jackets of the same age as that in the loading test. Along the y-axis, the bending stiffness was uniform over the entire length, but was evaluated as zero at every crossing point along the x-axis. The Young's modulus E of the artificial ground was estimated as $E = 210c$ (Takenaka, 1962), where c is the vane shear strength. Using this E value, the coefficient of subgrade reaction K was evaluated as the median of two values obtained by multiplying the following K by 1/4 and 1/3 (JSCE, 1986):

$$K = 1.58 \cdot \alpha \cdot E \cdot B^{-3/4}, \quad (1)$$

where $\alpha = 1$ and B is the diameter of the jacket. The orthogonal jacket crossings were modeled as points of elastic support. The spring constants of the supports were evaluated as the inverse of the maximum settlement generated on a single jacket in the orthogonal direction, applying a unit load (1 kN) at the middle point. In the calculations for the orthogonal direction, the points of support were not introduced.

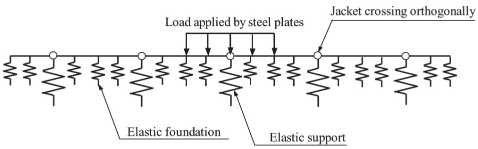

Figure 5. Numerical model for simulating the loading test.

Table 5. Physical parameters in the numerical simulations.

Bending stiffness of jackets	0.741 kN*m^2
Young's modulus of ground E	210 kN/m^2
Coefficient of subgrade reaction K	545 kN/m^3
Spring constant at elastic support	
Model along x-axis (Case-1)	180 kN/m
Model along y-axis (Case-1)	95 kN/m
Model along x-axis (Case-2)	50 kN/m
Model along y-axis (Case-2)	35 kN/m

The unit load mentioned above was applied two ways; namely, distributed over the length of the wooden base (Case-1) or concentrated at the center of the beam (Case-2). Thus, two cases of calculations with different values of spring constant were performed, in addition to a case with a spring constant of zero (Case-3).

The results of numerical simulations are shown in Fig. 4. It is seen that the calculated settlements of the base in two cases (Cases 1 and 2) are almost as large as the measured ones. These results support the simulation models. Comparing Cases 1 and 2 to Case 3, it is found that the settling is reduced by about 30 to 50% due to the orthogonally crossing jackets, and the reduction is limited to about 10 to 20% from the conventional sheet if the jackets were placed separately (i.e., not in the form of lattice-frame).

5 CONCLUSIONS

The main findings on the effectiveness of the lattice-frame-reinforced (LFR) sheet obtained from a set of loading tests and numerical simulations for locally affected loads are summarized as follows:

(1) The LFR sheet paved on very soft earth significantly decreases the differential settlement compared to a conventional sheet due to the load distribution effect of the rigid lattice-frame.
(2) The behavior of the LFR sheet can be accurately simulated numerically using the beam-on-elastic-foundation model.
(3) The jackets, although having large rigidity, are relatively ineffective unless they are applied in the form of lattice-frame.

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