6th Asian Regional Conference on Geosynthetics - Geosynthetics for Infrastructure Development, 8-11 November 2016, New Delhi, India

ROLE OF PRESTRESS IN GEOGRID OF CONFINED-REINFORCED EARTH METHOD TO MITIGATE BRIDGE APPROACH SETTLEMENT

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ABSTRACT

A new construction method, the confined-reinforced earth (CRE) method, has been proposed to reduce differential settlement due to earthquakes between bridges and their approaches. Obstructive differential settlement is often caused by large earthquakes; vehicles, especially emergency vehicles sometimes cannot pass the resulting unevenness. The CRE method consisting geogrid layers, confining tie rods, and granular soil (composite layer) is applied to the subgrade layer, at the bottom of paved roads. To improve performance of the CRE method, a series of laboratory prototype scale model tests was carried out to investigate the effects of prestress in the geogrid on mitigating the differential settlement between bridges and their approaches. The levels of prestrain applied to the geogrid were 0%, 0.016%, 0.05% and 0.1% in elongation. The results show that the prestress in the geogrid plays an important role in reducing differential settlement between bridges and their approaches.

1. INTRODUCTION

Earthquakes commonly induce settlement in the approach of bridge abutments due to slope movement or grainslip (Siddharthan and El-Gamal, 1996). In major seismic events, large deformations and significant differential settlement develops when liquefaction of the foundation occurs, resulting in cracking, settlement, lateral spreading and slumping (Tami 1996, Ali 1998; Manika and Akihiro 2014). Consequently, vehicles, especially emergency vehicles, cannot pass the unevenness created by the earthquake. To mitigate damage from earthquakes, the use of geosynthetic reinforced soil has been widely applied because of its high seismic resistance (Tatsuoka et al., 1997; Koseki, 2012). Furthermore, one important aspect of reinforced-soil is its potential to eliminate differential settlement (Monley and Wu, 1993; Helwany et al, 2003; Miao et al, 2004; Viswanadham and Konig, 2009). A new method, the confined-reinforced earth (CRE) method was proposed to mitigate this problem. CRE uses geogrid layers, prestressed steel tie rods and granular soil, applied to the subgrade layers, under the pavement of road structures. In this method, the reinforced soil is confined by the prestressed tie rods as shown in Figure 1. A full-scale field test was carried out to compare the behavior of road structures with the CRE method and the conventional method (without use of geosynthetics) due to differential settlement of 550 mm. The results of the two methods illustrated in Figure 2 show that the method with the CRE allowed the vehicle to pass while the other method did not do (Ohta et al., 2013). Later experiments (Kuwano et al., 2013) also proved that the CRE method effectively improved the stiffness of the subgrade layer and reduced differential settlement of the road pavement.

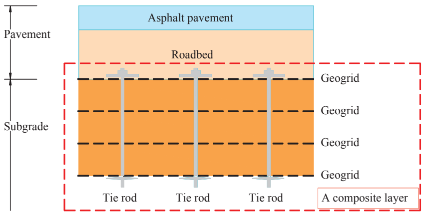

Fig. 1: Confined-reinforced subgrade (Kuwano et al., 2013)

Fig. 2: The results of road structures due to settlement, with (a) CRE method, (b) traditional method (Ohta et al., 2013)

However, geosynthetics demonstrate their beneficial effects only after large settlements (Shukla and Chandra, 1994a, b). This is due to the fact that for initial settlements, strains in the soil are insufficient to mobilize significant tensile load in the geosynthetics to support vertical loading (Shukla and Chandra, 1994a, b; Lovisa, 2010; Shivashankar and Jayaraj, 2013). Therefore, it is necessary to apply a technique that gives geosynthetics the capacity to support vertical loading in the absence of large deformation. It has been noted that the key point of the CRE method, which makes it different from common reinforced soil structures, is the confining tie rods. Prestress is introduced into the tie rods, contributing to the integrity of the reinforced soil that has high stiffness (Tatsuoka et al., 1997, Uchimura el al., 2003). As a result, it shows reduced deformation when subjected to differential settlement or traffic load (Shinoda et al., 2003). Therefore, the prestress in tie rods strongly affects the CRE deformation. There are three ways to create prestress in the geogrid: prestressed reinforced soil by compaction (PRSc), permanently prestressed reinforced soil (PRSp) and temporarily prestressed reinforced soil (PRSt) (C.Lackner et al., 2013). In this study, four laboratory model tests were carried out to investigate and evaluate the effects of prestress in the geogrid on the CRE deformation due to differential settlement. If prestress is applied and the stress (force) is controlled at the ends of a geogrid, it is difficult to control and keep uniform the stress along the geogrid. Meanwhile, the stress in the geogrid in realistic cases that its construction method is introduced in the conclusion shows uniform distribution along the geogrid. Therefore, instead of controlling prestress in the geogrid by stress (force) at both ends of the geogrid, strain (prestrain) in the geogrid was controlled based on attached the strain gauges on the geogrid. The levels of strain (prestrain) were set up at 0.00, 0.016%, 0.05% and 0.10% in elongation. The experiments and their results will be presented below.

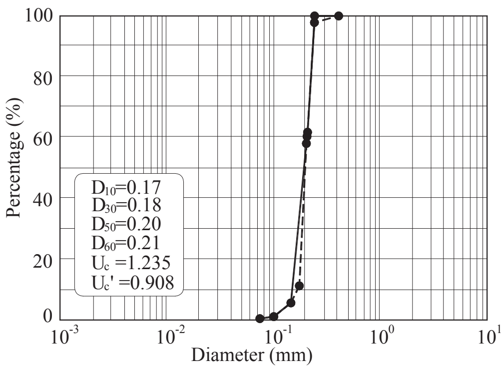

Fig. 3: Grain size distribution curve of Toyoura sand

2. CONFINED-REINFORCED EARTH TESTS

2.1 Material Properties

The geogrid used for the experiments was a biaxial geogrid with tensile strength of 200 x 5 kN/m (longitudinal x transversal), rupture strain at 4.5% and 26 mm x 28 mm (longitudinal x transversal) opening size. The granular soil used in the model was dry Toyoura sand (uniform sand) with specific gravity γ_s=2.645; e_{max}= 0.973; e_{min}=0.609; D_{50}=0.2 mm. The grain size distribution curve is shown in Figure 3.

2.2 Model Experiment

The model test setup is shown in Figure 4. The reinforced soil was constructed in a soil box with inner dimensions length x width x height = 120 cm x 40 cm x 80 cm. The composite layer was supported by two bottom plates, plate 1 and plate 2. Plate 1 was fixed on the frame (to simulate the abutment of a bridge) while the other plate was supported by jacks so that it could move down to simulate settlement of the embankment below the pavement. There were four geogrid layers (G1, G2, G3 and G4) with vertical spacing (Sv) of 5 cm. The lowest (bottom) geogrid layer, G4, was placed directly onto the plates. Strain gauges were attached at four points A, B, C and D in Fig. 4a) (at 0.3 m, 0.5 m, 0.7 m, and 0.9 m from left to right of the soil box, respectively) on geogrid layers G2, G3, and G4. No strain gauges were attached to G1 because it separated from the top sand layer during the test, which does not reflect realistic behavior. To measure both tensile strain and bending strain, two strain gauges in pairs were attached on both sides of each point, i.e., on the upper and lower surfaces of the geogrid. Tie rods were set with spacing of 80 cm in the longitudinal direction and 20 cm in the transversal direction. They were placed at 20 cm and 100 cm from the left to right of the soil box. It is noted that in order to keep the sand from leaking when the CRE deformed, the sand layers were wrapped in thin low strength geotextile.

2.3 Test Procedures

Four test cases were carried out and are shown in Table 1. All conditions of the four cases are the same except for the prestrain in the geogrid layers. A detailed description of the experimental procedure follows. In the first step, the lowest geogrid layer (G4), which was fixed at both ends by clamps, and four tie rods, R1, R2, R3 and R4 was placed onthe bottom plates,plate1 and plate 2. Next, the sand was poured from a height of 45 cm, using the multiple sieve techniqueto keep the same relative density of about 30%, and leveled. The other geogrid layers (G3, G2, and G1) and the uppersand layers were prepared in a similar way until completion. After the placement of the top geogrid (G1), anchors were connected to both ends of each geogrid. Both ends of the geogrids were prestressed to the desired prestrain value and then fixed at both sides of the soil box through pulleys in the horizontal direction so that the composite layer could move up or down by pulleys. The levels of prestrain in the geogrid were 0, 160, 500 and 1000 $\mu\varepsilon$ (0%, 0.016%, 0.05%, and 0.10% respectively). The maximum prestrain (0.1%) corresponds approximately to 2% of the tensile strength (2% * 200 kN/m = 4 kN/m); it is thus feasible to apply the experimental level of prestrain in practice. The same level of prestrain was introduced in the G1, G2, G3, and G4 geogrid layers in each case. Next, the tie-rods were preloaded to 3 kN. The CRE can work effectively if kept at high confining pressure but its sand does not reach failure state (Tatsuoka et al., 1997). The pressure on the sand can be calculated as force/area of the plate of the tie-rod = 3/(0.1*0.1) = 300 kN/m2 ≈3.06 kgf/cm2. This value of pressure is quite large and acceptable for fine sand. In the last step, plate 2 was lowered by jacks to induce differential settlement relative to plate 1. Lowering of plate 2 was stopped when it became detached from the CRE layer. The deformation of the CRE surface was measured manually. The strain of the geogrid, reaction at the left side of the soil box and the tensile force in tie rods measured by strain gauges and load cells were recorded by the data recorder during the test.

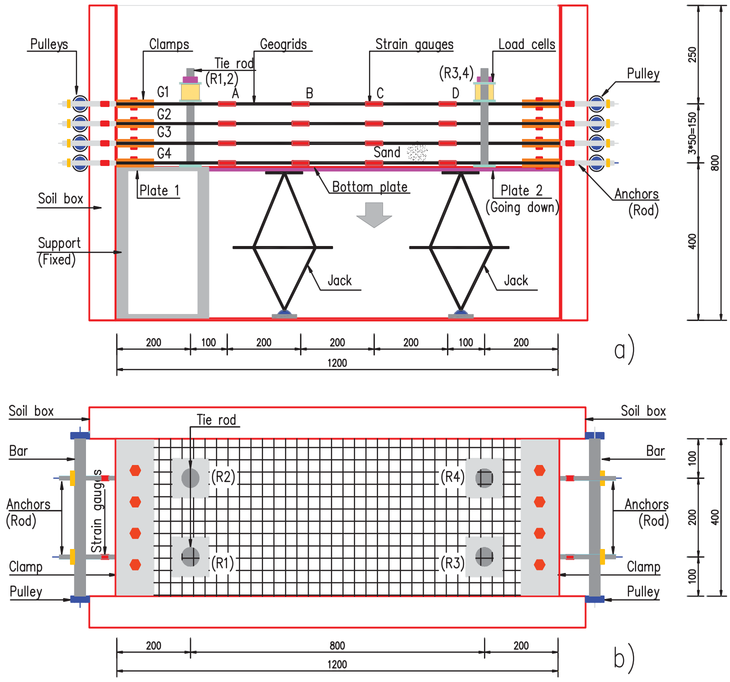

Fig. 4: Experimental model, (a): elevation view, (b): plan view

Table 1: Experimental cases

Cases	Sv (cm)	H (cm)	No. geogrid	Prestrain in geogrid
Case 1	5	15	4	0.000%
Case 2	5	15	4	0.016%
Case 3	5	15	4	0.050%
Case 4	5	15	4	0.100%

Sv: geogrid spacing, H: thickness of CRE

Table 2: Slopes of surface at 40cm, 60cm and 80cm

Cases	Slope of surface, i (°) at			Prestrain
	40cm	60cm	80cm	(%)
Case 1	5.99	7.12	7.12	0.000
Case 2	5.42	7.12	5.99	0.016
Case 3	4.28	5.71	5.99	0.050
Case 4	4.28	5.71	5.14	0.100

3. RESULTS AND DISCUSSIONS

3.1 Deformation

Surface deformation was measured at 10 cm intervals from left to right of the soil box as settlement up to 10 cm was simulated (Figure 5). The deformations in each case were compared to investigate the effect of prestress in the geogrid. As can be seen from Figure 6, the biggest deformation was observed in the case with the lowest prestrain level (0%) while the smallest deformation happened at the biggest prestrain level (0.1%) (8.7cm compared with 6.8cm). This is due to the fact that the deformation of the geogrid must increase until equilibrium between the tension in the geogrid and the vertical load (its weight) occurs. Therefore, the deformation of the case with the largest prestress due to differential settlement is smaller than those with lower prestress. The slopes of surfaces at 40 cm, 60 cm and 80 cm shown

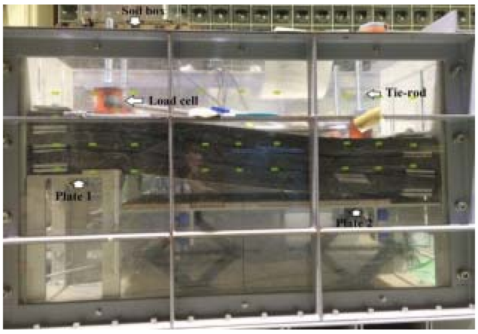

Fig. 5: Deformation of CRE due to settlement

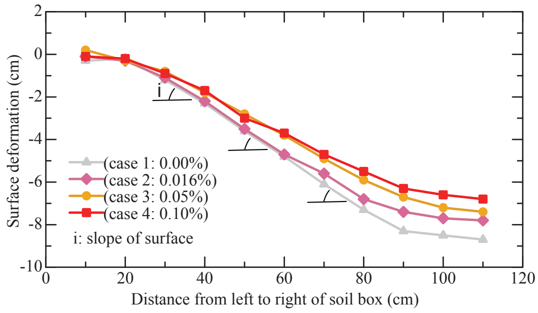

Fig. 6: Surface deformations due to settlement of 10cm.

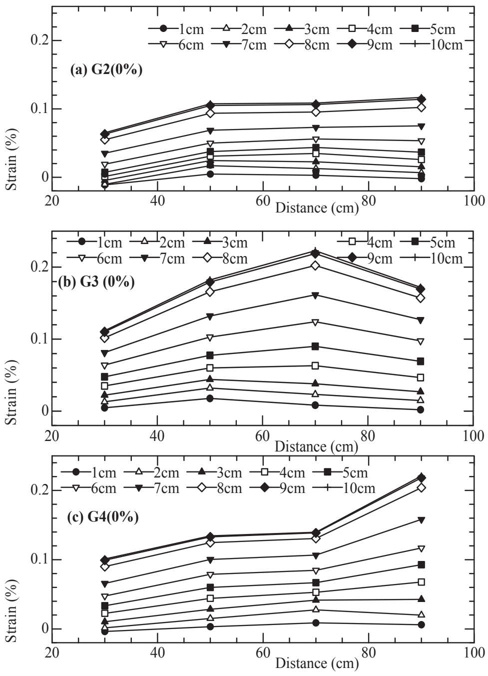

Fig. 7: Strain in geogrids (case 1: 0.0% of prestrain).

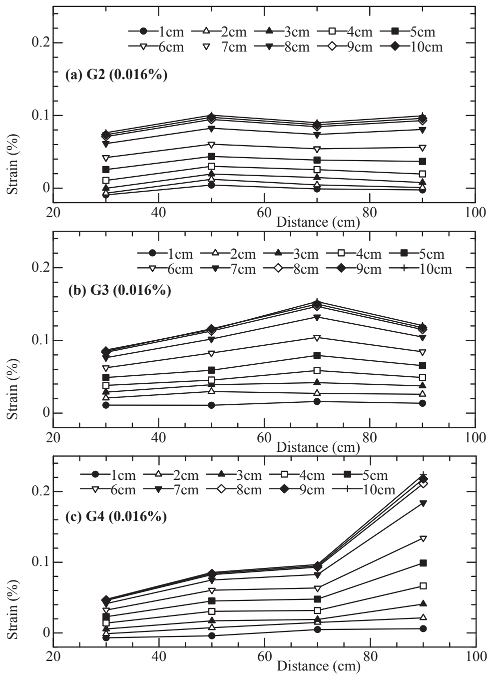

Fig. 8: Strain in geogrids (case 2: 0.016% of prestrain)

in Figure 6 and Table 2 also indicate that the maximum slope occurred in case 1 and case 2 while the minimum slope happened in case 3 and case 4. However, if the level of prestress (or prestrain) in the geogrid is too large, it is likely to break due to settlement or loading. Hence, the question of what is a reasonable level of prestress in the geogrid must be considered before it is applied.

3.2 Strain in Geogrid

Strain gauges at four locations (A, B, C & D) were used to measure the strain due to lowering (settlement) of plate 2 (from 1 cm to 10 cm), as shown in Figure 7 (case 1: 0.0%), Figure 8 (case 2: 0.016%), Figure 9 (case 3:0.05%) and Figure 10 (case 4:0.1%). A positive strain value indicates tension of the geogrid, while a negative one means compression. The behavior of the CRE can bethe other cases, and then remained almost unchanged. The explanation is that when the settlement took place, the CRE thickness decreased because the CRE length was stretched due to inferred from Figures 7, 8, 9, and 10, and

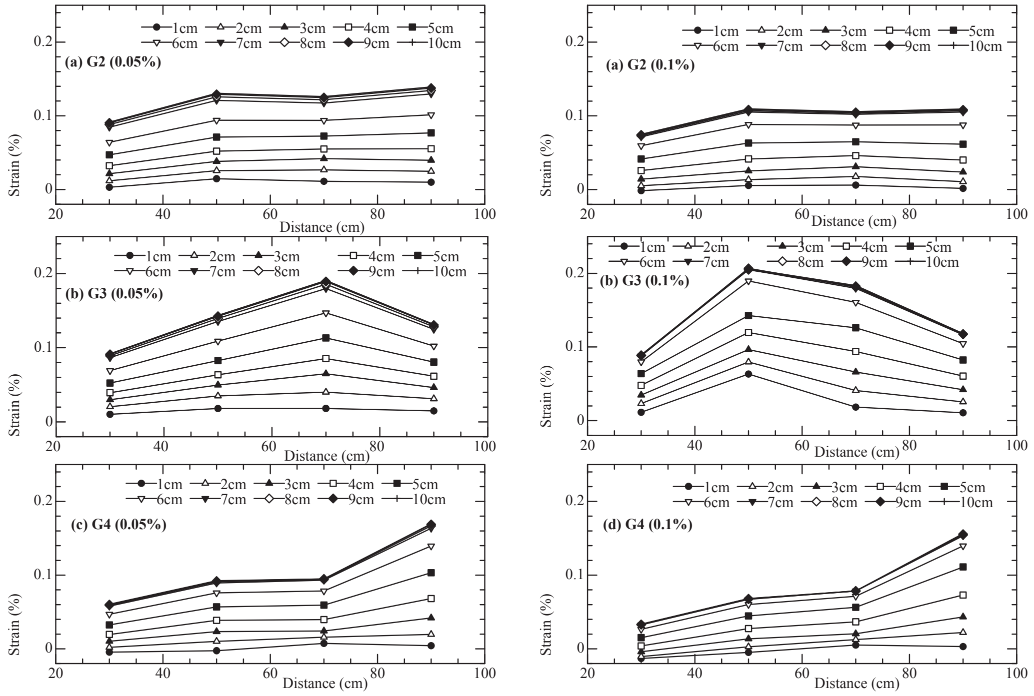

Fig. 9: Strain in geogrids (case 2: 0.016% of prestrain)

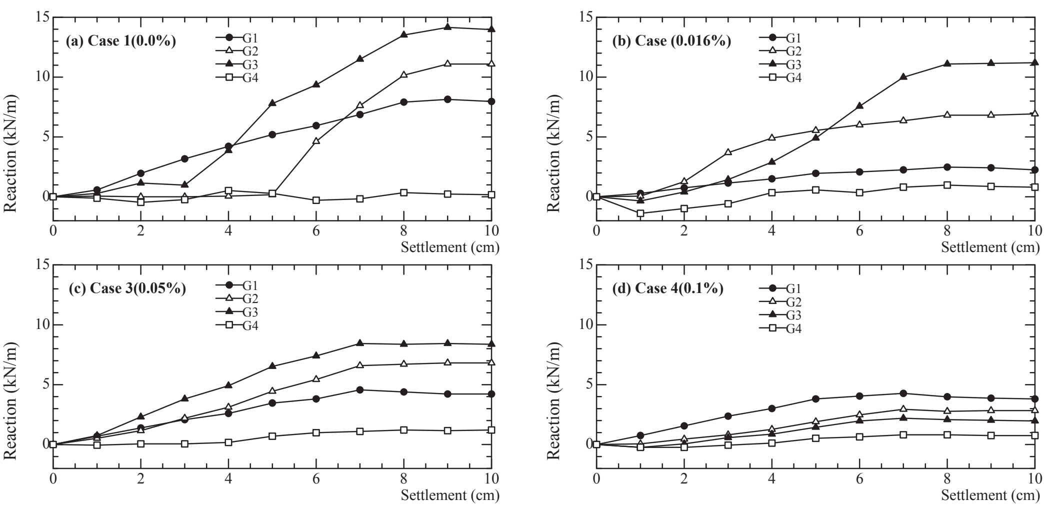

Fig. 11: Reaction force at left side of soil box:
(a): Case 1-0%, (b) case 2-0.016%; (c) case 3-0.05% & (d) case 4-0.1%

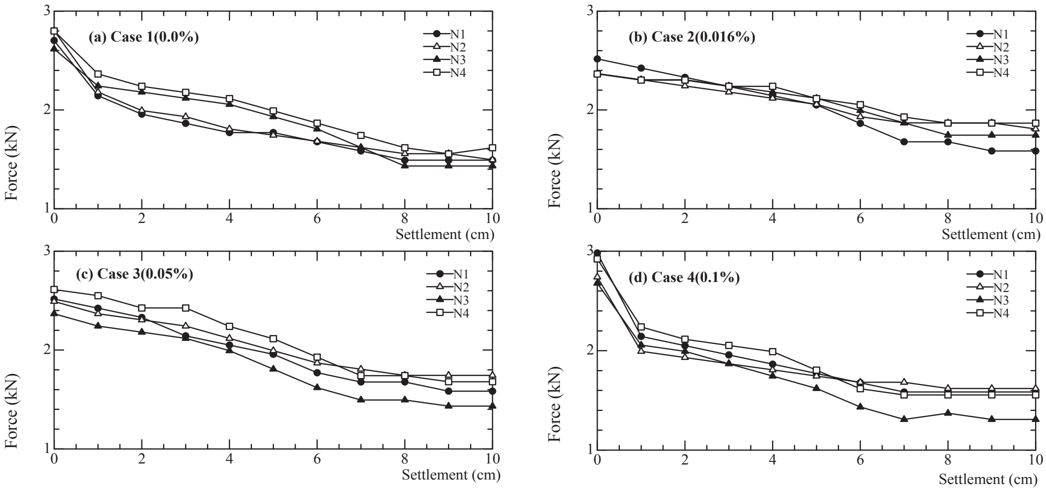

Fig. 12: Force in tie-rods: (a): Case 1-0%, (b) case 2-0.016%; (c) case 3-0.05% & (d) case 4-0.1%.

interpreted as follows. The tensile strain in the geogrid increased with the increase in settlement. Some of the strain was below zero when settlement was small, but above zero for large settlement. This was because the two paired strain gauges were not installed at exactly opposite locations at each point (slight difference). Consequently, when settlement was small, bending deformation affected average strain. This resulted in a small error. This error became negligible for large settlements. This means that the geogrid showed tensile deformation in general due to the settlement. It also shows that the strain in G2 was the smallest while it was bigger in G3 and G4. The reason is that G3 and G4 were below G2 and supported more weight of sand than G2. When the settlement reached a certain value (e.g. 9 cm in case 1(0%), 7 cm in case 4(0.1%)), the strain no longer increased with the increase in settlement. This is because the weight of the CRE was supported by tension in the geogrid – the membrane mechanism of the geogrid (Zornberg et al, 2007). Therefore, when tension was strong enough to support the weight, strain remained constant. This is an advantage of prestressed geogrid, which reduces the deformation due to settlement as compared to the case of a geogrid without prestress. The difference in the strain occurring in the geogrid among the cases was not clear even if the total amount of strain at A, B, C, and D of G2, G3, G4 of case 1 was higher than those of the case 3 and case 4 (i.e. 1.681% compared to 1.461% and 1.332%, respectively). This may be due to the fact that the number of strain gauges attached to the geogrid does not suffice to compare the deformation of the CRE.

3.3 Reaction of Geogrid at the Left Side of the Soil Box

The reaction of the geogrid at the left side of the soil box was analyzed because this force is an important factor affecting the behavior of the abutment. The reaction value of the geogrid layers (G1, G2, G3 & G4) of the four cases due to settlement was measured and is shown in Figure 11. As illustrated in the figure, the level of reaction of the four cases depended on their deformations and increased with settlement. The highest reaction was observed in the case with the biggest deformation (case 1) while the lowest reaction occurred in the case with the smallest deformation (case 4). In the first three cases 1, 2 and 3, reaction in G3 was the highest and it was suitable for its strain. This is because the geogrid deformed to support vertical loading by the membrane effect; therefore, the lower geogrid layers support more the weight of upper sand layers. As a result, the reaction of G3 was higher than that of G2. By contrast, reaction of G4 was the smallest because of high skin friction between the geogrid and the sand, geogrid and the bottom plate. In case 4, with the highest prestrain applied, the total reaction due the settlement was the smallest.

This can be explained by the fact that its deformation was the smallest, resulting in the smallest tension in the geogrid due to settlement.

3.4 Force in Tie Rods

Figure 12 shows the force in the four tie-rods measured by load cells when settlement occurred. The tie rods were preloaded to 3 kN, which force then decreased before settlement because of the stress relaxation of the soil. As indicated in figure 12, the force decreased between 1 cm and 8 cm of settlement in case 1 and between 1 cm and 7 cm of settlement in the other cases, and then remained almost unchanged. The explanation is that when the settlement took place, the CRE thickness decreased because the CRE length was stretched due to settlement and the CRE's volume probably decreased due to shearing of loose soil. This value was unchanged when the deformation remained constant. Also, the decrease in force in tie-rods is not affected by prestress in the geogrid. To keep high tensile force in tie rod that leads to high stiffness of soil, creep deformation should be allowed to occur under the prestressing condition (Tatsuoka et al., 1997) and soil should be well compacted, so it will dilate when shared due to differential settlement.

4. CONCLUSIONS

Experiments were carried out to investigate the effect of prestress in the geogrid on CRE deformation. The following conclusions were obtained from the test results:

1) Prestressing the geogrid reduces the deformation of the CRE due to differential settlement, this may make it possible for vehicles to pass unevenness after earthquakes under some conditions.
2) Strain in the lower geogrid layer is bigger than in the upper geogrid layer; however, the difference is not particularly large. This can be considered as an advantage conferred by the confining tie rods, which redistribute stress and strain in geogrid layers to support vertical loading. The prestress also reduced the reaction on the soil box's left side.
3) The tensile force in the tie-rod reduced due to the settlement. Hence, the effect of confining the sand to improve shearing resistance of the CRE was reduced.

In practical applications, prestress is applied instead of prestrain because this is easier for construction. To apply prestress in the geogrid of the CRE method, both ends of the geogrid are held by clamps. The geogrid is constructed after the construction of the layer beneath the CRE is completed. One end of geogrid is fixed to the abutment of a bridge, the other end is pulled out by machines to reach the desired prestress in the geogrid and then fixed by pins to the ground (the pins fix clamps keeping the geogrid layers to the ground). It is clear that stress distribution in the geogrid is almost uniform because it is not affected by any subgrade layers when prestress is applied. After that, the next subgrade and geogrid layers are constructed. The length and spacing of pins is chosen based on the level of prestress desired.

Geogrid creep was not taken into account in the experiments; the tests took place soon after construction of the setup. In particular, the prestrain in geogrid layers was introduced for only 20~30 min and the settlement began immediately after that

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