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Laboratory and numerical modeling of strip footing on geotextile-reinforced sand with cement-treated interface

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This paper presents the results of a laboratory and numerical study on the effects of cement treatment of the interface between geotextile and sand on the bearing capacity of a foundation built on geotextile-reinforced sand. The bearing capacity of a 25 cm × 7.5 cm strip footing on a 90 cm × 25 cm × 30 cm sand box reinforced using a single-layer reinforcement of different lengths including, 20, 30, 45, 60, 75 and 90 cm, was studied in a laboratory. A cement-treated zone was created on the geotextile to improve the friction and adhesion of the interface zone. Tests were also conducted on reinforced soil without a cement-treated zone and the results were compared. A finite element model was calibrated and used for further studies. The results of the laboratory tests indicated that cement treatment of the interface between the geotextile and sand increases the bearing capacity of the foundation by 6%–17%, depending on the length of the reinforcement. The effectiveness of the cement-treated interface on improving of the bearing capacity is more evident with shorter-length reinforcements. For a certain bearing capacity, the required length of the reinforcement was reduced by approximately 40% when the interface zone of the sand and reinforcement was cement-treated. The effect of the cement-treated zone on the bearing capacity was more evident in low settlement levels, and decreased as the length of the reinforcement increased.

1. Introduction

The mechanical properties of soil as a granular material depend on its friction, cohesion, interlocking, and confinement. The inclusion of geosynthetics as a mechanical stabilization method improves the mechanical properties of soil (Shukala and Yin, 2006). Geosynthetics are widely used to improve the performance and stability of fills and foundations (Wu and Pham, 2013; Miao et al., 2014). The application of an adequate tensile reinforcement within a soil mass can enable it to retain both itself and the added surcharge (Yang et al., 2016). The contribution of reinforcements to the bearing capacity of a foundation is dependent on the occurrence of settlements, and is not notable for small-strain elastic deformations (McCartney and Cox, 2013). The bearing capacity or stability of geosynthetic-reinforced systems is governed by three criteria: axial failure, pullout, and the sliding of the reinforcements (Shukala and Yin, 2006). The required axial load capacity for reinforcements can be provided using high-strength or multilayer reinforcements (Ouria et al., 2016). To utilize the axial capacity of high-strength geosynthetics, a high pullout capacity is also required for the reinforcements. The pullout mechanism is the result of the relative sliding of the reinforcement with respect to the confining soil at the interface zone. The pullout capacity of geosynthetics depends on the normal stress, anchorage length, interface friction angle, and adhesion. Therefore, the number of reinforcement layers, as well as the reinforcement length, axial load capacity, interface properties, and embedment depth are influential parameters in improving the bearing capacity of a foundation built on geosynthetic-reinforced soil.

Increasing the number of reinforcement layers increases the ultimate bearing capacity at a decreasing rate (Basudhar et al., 2007; Tafreshi and Dawson, 2010); however, additional reinforcement layers are not very effective in settlement reduction (Basudhar et al., 2007). Guido et al. (1986) reported a 12% increase in the bearing capacity of a foundation placed on a two-layer planer reinforcement when compared to the bearing capacity of the same foundation placed on a single layer of reinforcement located at a depth 0.25-times greater than the foundation width. Tafreshi and

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Dowson (2010) reported a 50% increase in the ultimate bearing capacity when two layers of planer reinforcement were used instead of a single layer. The different bearing capacities reported in these experiments could be the result of using different materials, reinforcement lengths, and depths. Chen and Abu-Farsakh (2015) developed an analytical method to calculate the effect of the number of reinforcement layers on the bearing capacity of strip footing in terms of the number of layers, the depths of the reinforcements, and other parameters. Increasing the length of the reinforcements improves the ultimate bearing capacity of the foundation up to a certain limit, at which point a further increase shows no additional improvement (Cicek et al., 2015). The optimum length of the reinforcements for a maximum increase in bearing capacity is 3- to 6-times the foundation width (Abu-Farsakh et al., 2013; Cicek et al., 2015).

The depth of the reinforcement is another parameter influencing the bearing capacity of a foundation. The suggested optimal depths of the first and last layers of reinforcement are approximately 0.33–0.5- and 1.25-times the foundation width, respectively (Abu-Farsakh et al., 2013). The type of reinforcement is also an important factor in the improvement of the bearing capacity of the foundation (Ferreira et al., 2015). A single-layer geogrid reinforcement will increase the bearing capacity of the foundation by 10–15% in comparison to a single-layer geotextile reinforcement (Guido et al., 1986; Tafreshi and Dawson, 2010).

To increase the bearing capacity of a foundation, depending on the geometrical limitations, increasing the anchorage length is not always a feasible option. Mechanical anchorage or chemical bonding can be used to increase the interlocking, friction, and adhesion of the soil and geosynthetic materials applied, thereby increasing the bearing capacity of a foundation built on reinforced soil. A corrugation of reinforcement strips was used to improve the pullout capacity of the reinforcements (Racana et al., 2003). Taghavi and Mosallanezhad (2016) proposed a grid-anchor system to improve the ultimate bearing capacity of foundations placed on geogrids. Ebadi et al. (2015) used cement treatment to increase the interface shear strength of soil and a non-woven geotextile. A limited number of studies have been conducted on the effects of cement treatment of the interface between the soil and reinforcement on the bearing capacity of a foundation. The objective of the present study was to investigate the effects of the cement treatment of the soil-geotextile interface on the bearing capacity of foundation built on reinforced soil.

In recent years, concrete canvas or fabric and fiber reinforced concrete have been developed for application in the geotechnical engineering field (Colombo et al., 2013; Li et al., 2016). Concrete canvas is a flexible cement powder permeated fabric that hardens when hydrated and changes into a thin, durable, waterproof, and fire-resistant concrete layer (Li et al., 2016). When a layer of cement-treated sand is placed on the geotextile, the resulting composite material will be similar to concrete canvas but not exactly the same. Although textile and fibers were originally applied to concrete canvas to increase the tensile strength and flexibility of the concrete, in the present research, cement is used to increase the roughness, interface friction, and adhesion at the interface between geotextile and sand. A cemented material adheres to the geotextile surface, and produces a firm cemented layer on the geotextile, thereby transferring the slip surface from the sand-geotextile interface to the cemented zone and sand interface. Cement is a very cheap and plentiful material in Iran, whereas geotextile is more expensive than cement. This procedure can be employed to reduce the anchorage length required in reinforced soil systems. A similar procedure using epoxy resin was employed by Toufigh et al. (2016) to improve the interface behavior between sand and carbon fiber reinforcement sheets. They used an epoxy resin to adhere the sand particles to the surface of carbon fiber sheets to produce a rough surface.

In this study, laboratory tests were conducted on geotextile-reinforced soil with and without a cement-treated interface, and the results were compared. In addition, a numerical model was calibrated and used to model the effects of the cement treated zone on the bearing capacity of the footing.

2. Materials and methods

2.1. Sand

The sand used in this study was collected from an area northeast of Ardabil city in Iran, and was classified as poorly graded in Unified Soil Classification system according to ASTM D2487-11 (2011). The internal friction angle of the sand was determined using a direct shear test according to ASTM D3080-04 (2004), whereas the moisture content and unit weight of the sand were determined based on ASTM D2216-05 (2005) and ASTM C127-07 (2007), respectively. The basic properties of the sand are given in Table 1.

2.2. Geotextile

Non-woven geotextile was used in this study as reinforcement. The cement-treated geotextiles were saturated using distilled water, followed by the spraying of 1.5 kg/m^2 of Portland cement onto the surface using a salt shaker, with a sand layer placed on top. Both sides of the geotextile were treated in the same manner. The water absorbed by the geotextile permeated the cement and sand layers initiating the hydration process of the cement. The composite material was cured at room temperature (20 °C) for one week. Hydration of the cement layer produced a cemented zone adhering the sand particles to the geotextile and producing a rough surface. The thickness of the cement treated zones adhering to the geotextiles was approximately 1.5–3 mm. The cement treatment procedure for the geotextile used in this research is shown in Fig. 1.

The axial load capacity and elastic modulus of the geotextile were determined in a laboratory according to ASTM D4595-11. The results of the tensile tests of the cement-treated and pristine geotextiles are shown in Fig. 2.

The interface friction angles of the cement-treated and pristine geotextiles were determined in the laboratory according to ASTM D5321/D5321M-14 (2014). The failure envelope of the interface shear tests of the pristine and cement-treated geotextiles and sand are shown in Fig. 3.

The mechanical properties of the pristine and cement-treated geotextiles and their interface with sand are listed in Table 2.

2.3. Experiment setup

A test setup consisting of a steel box, a loading device, and measurement instruments was used in this study. The internal

Table 1
Basic properties of the sand.

D_{10} (mm)	0.4
D_{30} (mm)	0.6
D_{60} (mm)	1.2
C_U	3
C_C	0.75
w	2%
ϕ	35°
γ	16.1 kN/m^3

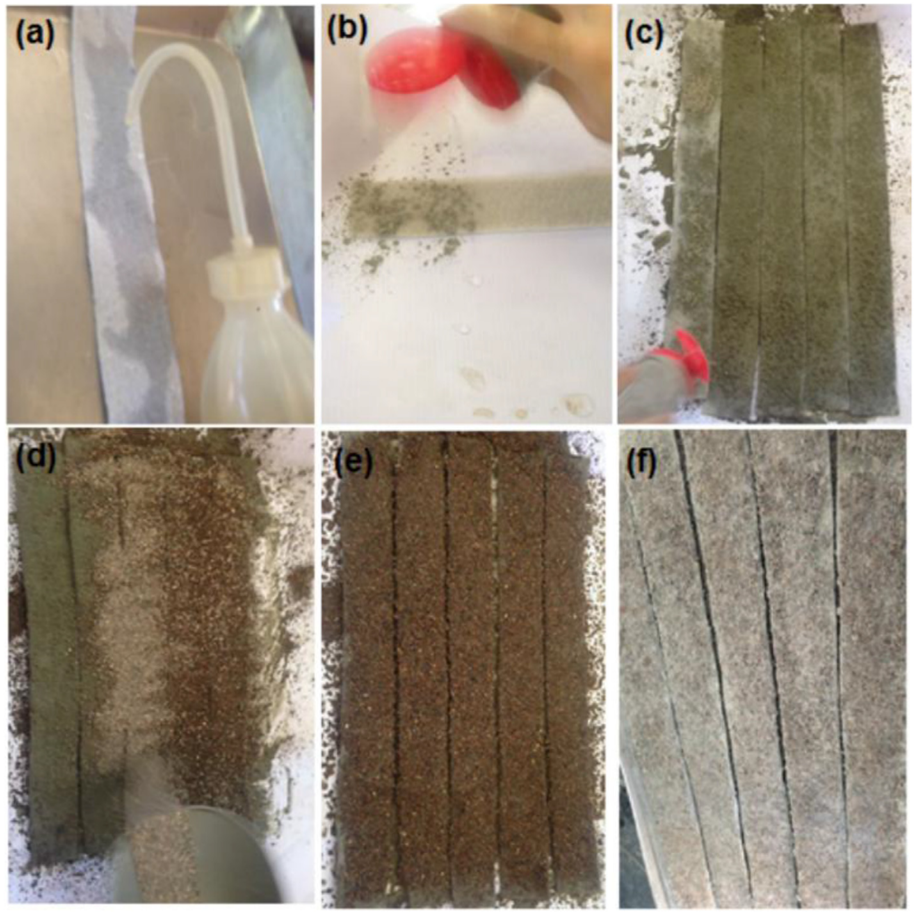

Fig. 1. Geotextile surface treated with cement and sand.

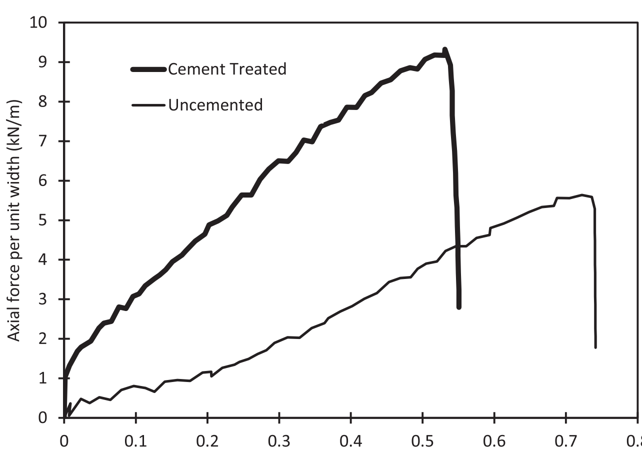

Fig. 2. Axial loading curves of cement-treated and pristine geotextiles.

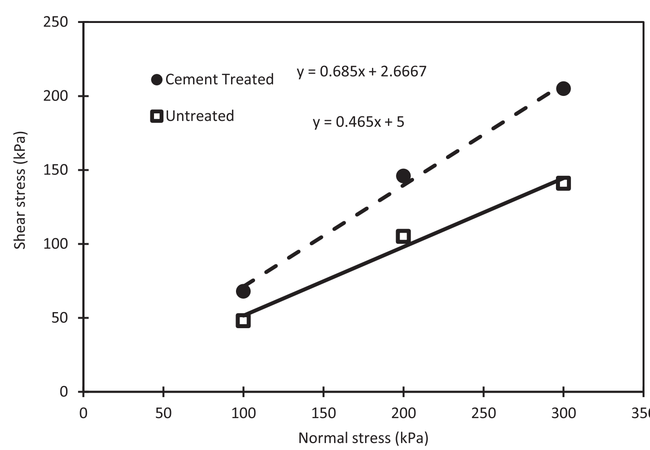

Fig. 3. Interface shear strength of sand and geotextile, and sand and cement-treated geotextile.

dimensions of the steel box were 90 cm (length) × 30 cm (height) × 25 cm (width). The box was made of 0.5-cm-thick steel plates, and its front wall was made from 1-cm-thick marked polyflex glass. The inside of the box was polished to reduce the wall friction effect. Two U-shaped steel supports were used to prevent lateral expansion of the box, and a steel plate was used as the strip footing. The footing length, width, and thickness were 25, 7.5, and 1.5 cm, respectively. Both sides of the footing were loaded using two 10 kg weights in a 20 cm × 25 cm area. A CBR test apparatus was used as the loading and measurement device. Diagrams of the test box and loading device, and photographs of the test setup, are shown in Fig. 4.

3. Preparation and test procedure

The most important aspect of an experiment study is the ability

Table 2
Mechanical properties of pristine and cement treated geotextiles.

	Axial load capacity (kN/m)	Extension at failure (%)	Elastic modulus (kN/m)	Unit mass (kg/m^2)	Interface friction angle (°)	Interface adhesion (kPa)
Pristine Geotextile	5.29	74%	7.59	0.3	25	5
Cement-treated geotextile	9.17	55%	16.67	7	34.4	2.7

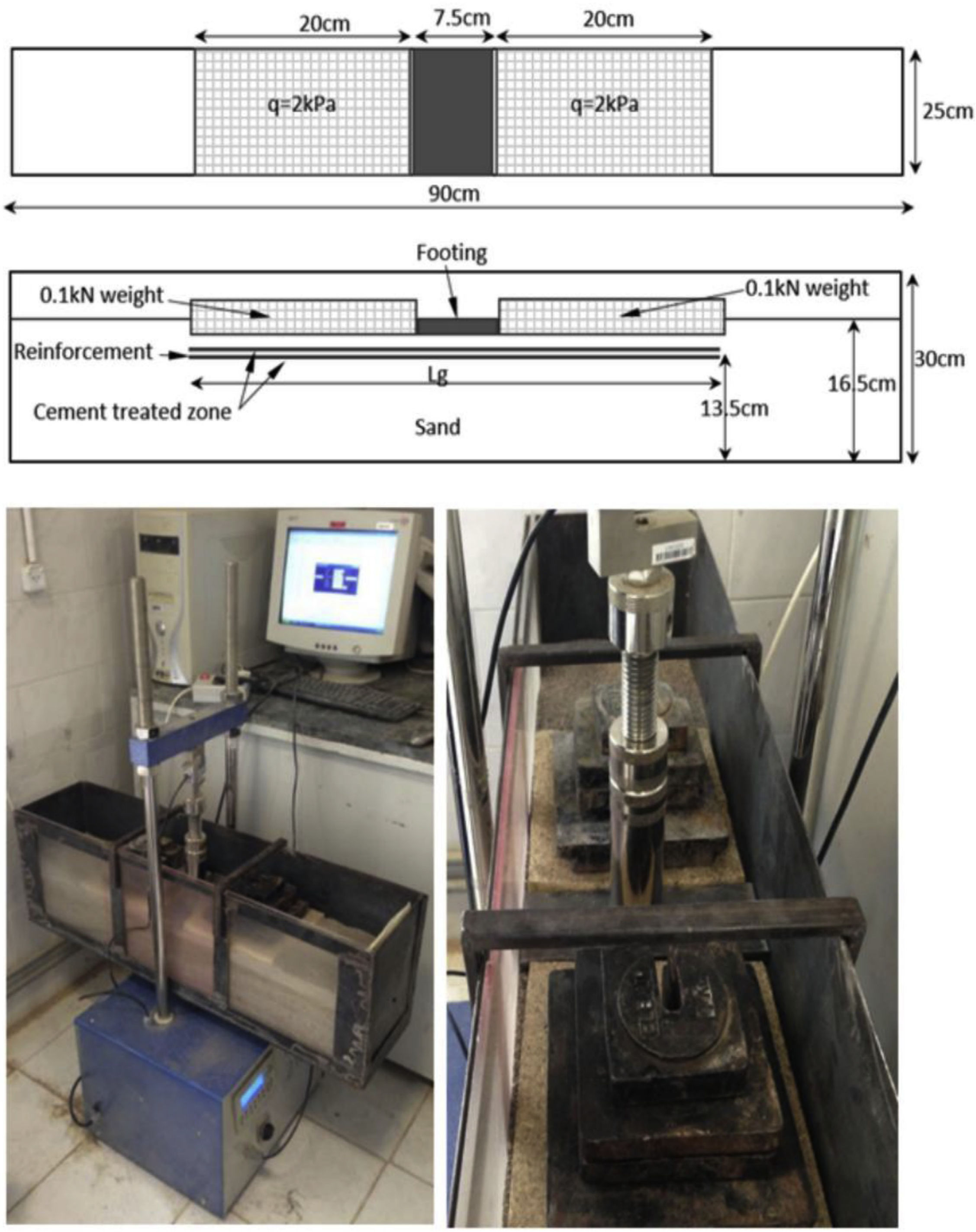

Fig. 4. Diagram and photographs of test setup.

to produce similar specimens (i.e., repeatability). The average unit weight of the sand in the test box was considered as a control criterion equal to 16.1 kN/m^3. To achieve similar average unit weights during the tests, 60 kg of sand was used in each experiment with similar dimensions. The sand was placed in four layers in the box. The weights of the first and second layers were 18.2 kg. The weights of the sand used for the third and fourth layers were 13 and 10.6 kg, respectively. The thicknesses of the first, second, third, and fourth layers were 5, 5, 3.5, and 3 cm, respectively. The geotextile layer was placed between the third and fourth layers. Each layer was compacted using a 14 cm $\times$ 14 cm square plate with a 3.8 kg weight dropped 50 times on each layer from a height of 15 cm. Because a portion of the compaction energy of the upper layers was transmitted to the lower layers, the initial thicknesses of the upper layers were taken less than those of the lower layers. The footing was loaded at a rate of 1 mm/min. The same procedure was used for the preparation of all models. Tests were conducted on both unreinforced and reinforced sand using six different reinforcement lengths, namely, 20, 30, 45, 60, 75, and 90 cm, in both cement-treated and pristine conditions. Each test was conducted three times, with the average of the three experiments considered the final result of the test. It should be noted that some of the tests were conducted more than three times to obtain repeatable results. Because the presence of reinforcement layers is not notable in small settlements (McCartney and Cox, 2013), the ultimate bearing capacity of the foundations was considered to be the bearing pressure for a settlement of 14 mm (near the maximum displacement of the loading device), or the point at which the load-settlement curve becomes horizontal.

4. Laboratory results

Fig. 5 shows the deformations of the foundation and reinforcement at the end of the laboratory test. The deformed shape of the geotextile is illustrated in Fig. 5 (b). It can be seen that the deformation of the reinforcement is localized near the edge of the foundation.

The results of the tests conducted for different reinforcement lengths without cement treatment are illustrated in Fig. 6. The vertical axis is the bearing pressure. It can be seen that the geotextile reinforcement has improved the bearing capacity and reduced the settlements of the footing.

Fig. 7 shows the test results of the unreinforced model, reinforced model, and model reinforced with a cement-treated interface for a 30-cm reinforcement length. The results of these tests show that reinforcement with a cement-treated interface is more effective than reinforcement without a cement treatment. The ultimate bearing capacity of the footing for the 14-mm settlement was improved by 80% when compared with the unreinforced condition using a layer of 30 cm reinforcement, and was improved by 100% when using the same reinforcement with 1.5 kg/m^2 of cement treatment. In addition, the reinforced model with the cement-treated interface has smaller settlements at the same pressure when compared to the reinforced model without a cement-treated interface.

The results of the model tests reinforced using different reinforcement lengths of a cement-treated interface are illustrated in Fig. 8. A comparison of Figs. 8 and 6 shows that the ultimate bearing capacities of all models with similar reinforcement lengths are higher when the interface of the geotextile and sand was treated using cement.

Fig. 9 shows the bearing pressure ratio (BPR) of models reinforced using cement-treated geotextile compared to that of models reinforced using pristine geotextile at different settlements. It can be seen that the effects of the cement treatment on improving the bearing pressure of the footing are more evident at lower settlements. Therefore, cement treatment can be used to decrease the settlements of geotextile-reinforced foundations.

The average values of the ultimate improving ratios (UBPR) of reinforced footings with and without a cement-treated interface are illustrated in Fig. 10. In this figure, UBPR is the ratio of the ultimate bearing capacity of reinforced footing to unreinforced footing for a 14-mm settlement, Lg is the length of the reinforcements, and B is the width of the footing. It can be seen that the reinforced footings with a cement-treated interface have a larger bearing capacity. Increasing the length of the reinforcements increases the ultimate bearing capacity while reducing the improvement rate for both cement-treated and untreated models.

The ratio of the ultimate bearing capacity of reinforced footings with a cement-treated interface compared to the reinforced model without a cement-treated interface (UBPRC) is illustrated in Fig. 11. It can be seen that the effect of the cement-treated interface on the bearing capacity of the foundation decreases as the length of the reinforcement increases.

Guido et al. (1986) and Tafreshi and Dawson (2010) reported a 10–15% increase in the bearing capacity of a foundation built on geocell-reinforced sand when compared with the same footing built on geotextile-reinforced sand. As can be seen in Fig. 11, cement

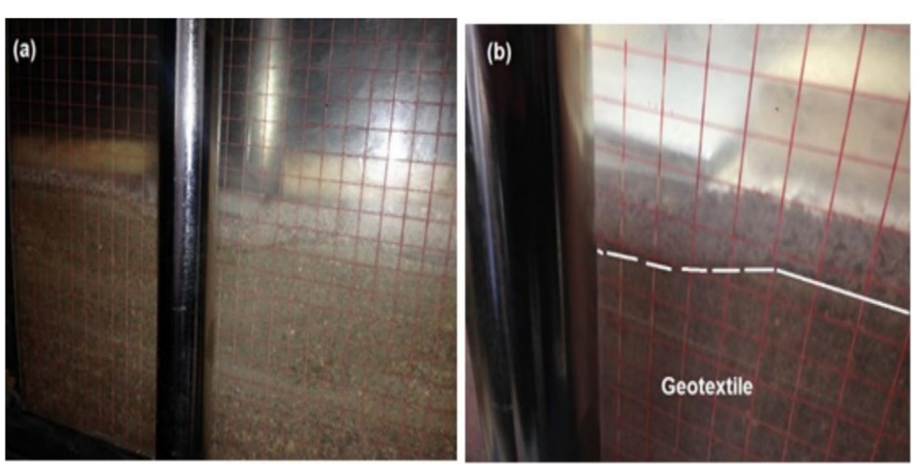

Fig. 5. Deformations of sand and geotextile layer after loading.

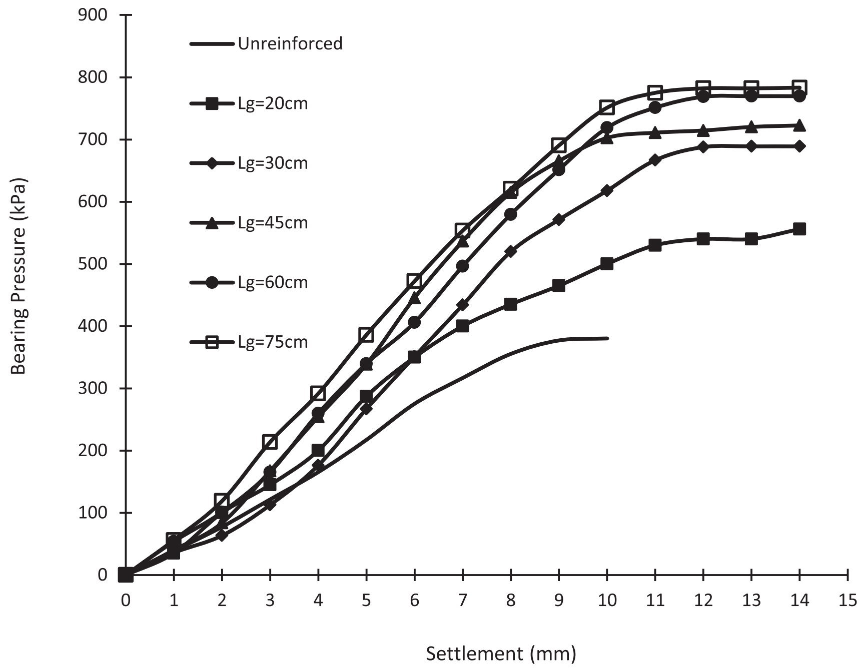

Fig. 6. Results of model tests on unreinforced and reinforced models with different reinforcement lengths.

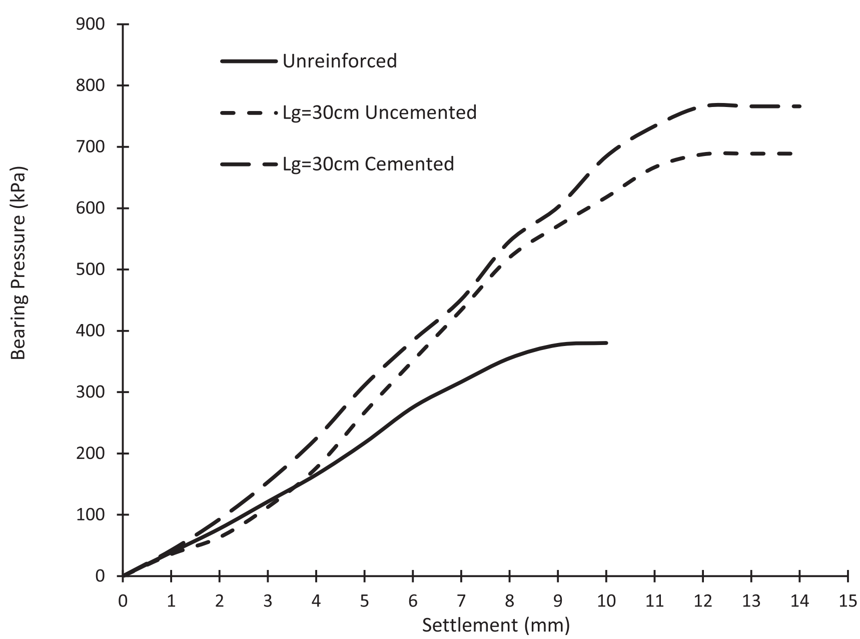

Fig. 7. Results of tests on unreinforced and reinforced models, and model reinforced with cement-treated interface with 30 cm reinforcement length.

treatment of the interface zone improved the bearing capacity by 6–17%. Therefore, geotextile reinforcement with a cement-treated interface can be used instead of a geocell or geogrid reinforcement.

For equal bearing capacity of the strip footing on reinforced sand, the required lengths of cement-treated geotextile versus pristine geotextile is illustrated in Fig. 12. Cement treatment of the interface of the reinforcements reduces the required length to achieve a certain bearing capacity. It can be concluded from Fig. 12 that the treatment of the interface zone of geotextile with 1.5 kg/m^2 of cement reduces the length of the reinforcement by approximately 40%.

5. Numerical modeling

The experimental test results were modeled using the finite element method (FEM), which can be used to simulate the mechanically stabilized soil structures (Rowe and Liu, 2015; Ouria et al., 2016; Ambauen et al., 2016). A link element was used for geotextile sheets (Chakraborty and Kumar, 2015). However, link elements can only bear axial tension. The von Mises model was used to describe the elastic–plastic behavior of the geotextile. In addition, the Mohr–Coulomb elastic–plastic model was used for sand. This model is simple and sufficiently accurate for non-

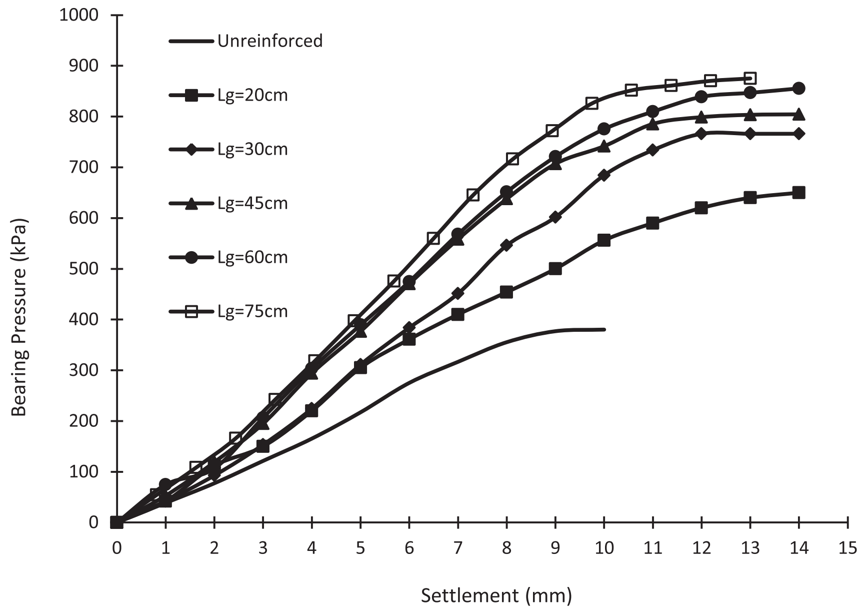

Fig. 8. Results of tests on unreinforced and reinforced models with cement-treated interface with different reinforcement lengths.

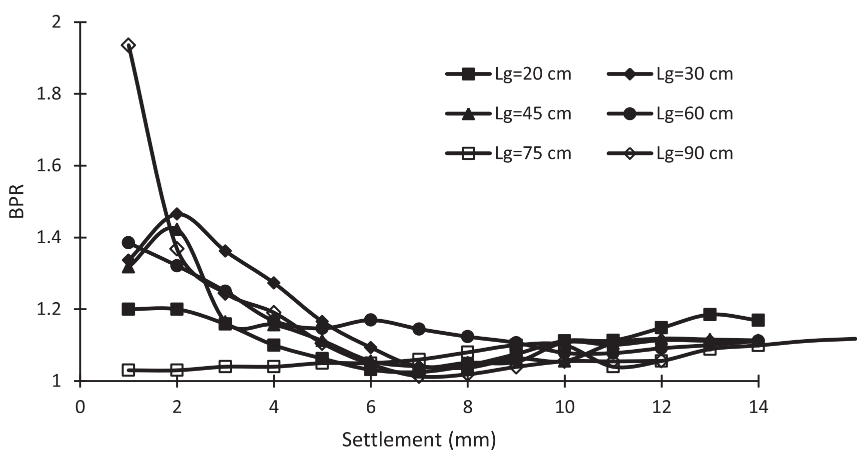

Fig. 9. Ratio of bearing pressure of reinforced models with cement-treated interfaces to the bearing pressure of reinforced models with pristine geotextile at different settlements.

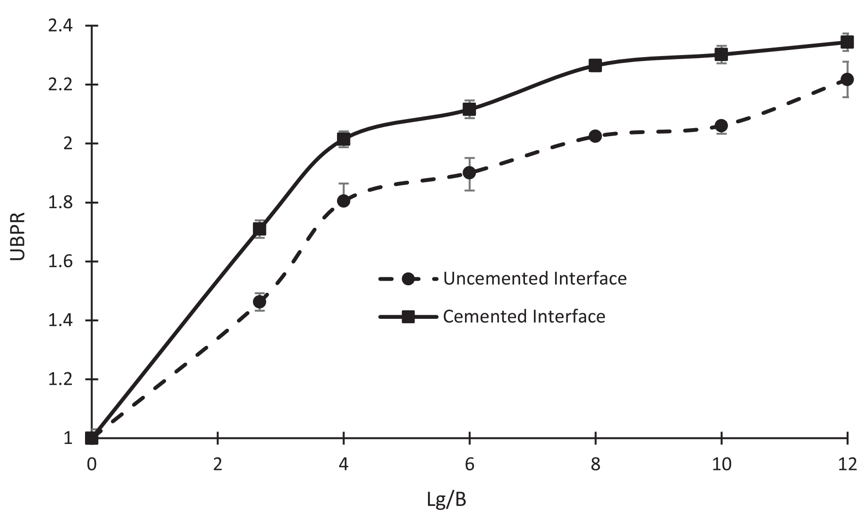

Fig. 10. Ratio of improvement in ultimate bearing capacity of reinforced models with and without cement-treated interfaces for 14 mm settlement.

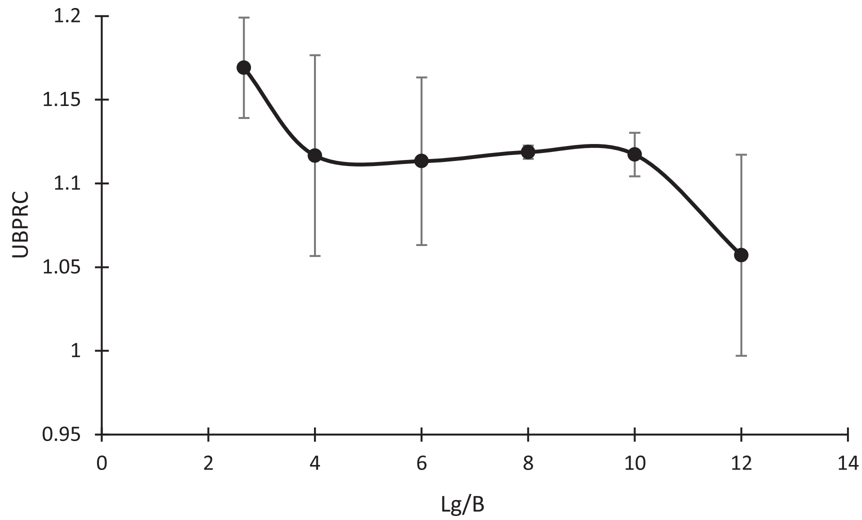

Fig. 11. Effect of cement-treated interface on the improvement of ultimate bearing capacity of reinforced soil.

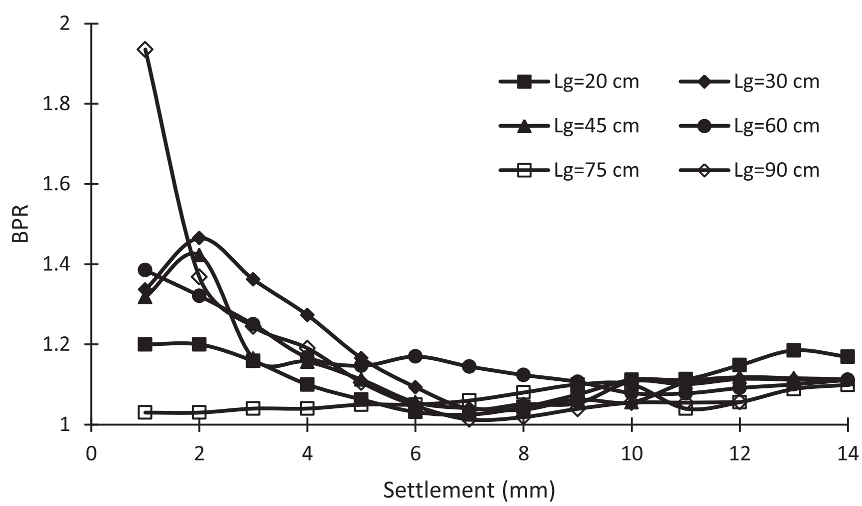

Fig. 12. Equivalent length of geotextile with and without cement-treated interface for a certain bearing capacity.

cohesive soils (Zheng and Fox, 2016; Oliaei and Kouzegaran, 2017). The internal and interface friction angles of soil, soil-geotextile, and cement-treated soil geotextile are tabulated in Tables 1 and 2 The Poisson's ratio of the sand was taken as 0.15 and its elastic modulus was calculated using a back analysis method based on the results of the unreinforced test model (E = 20,000 kPa). Strip footing was modeled on reinforced sand using 30 cm of geotextile with and without a cement-treated interface. The FE model and the mesh of the test model are shown in Fig. 13. Because the test setup was symmetric, only the right-half side of the laboratory model was simulated in the numerical model to minimize the computational requirements (Hegde et al., 2015).

The results of the numerical analysis of strip footing on unreinforced sand are provided in Fig. 14. It can be seen that the numerical model predicted the ultimate bearing capacity of the footing with an 8% error, which likely resulted from the material model employed in the numerical analysis, which was based on the linear elasticity prior to failure. Although at low settlements the bearing pressure calculated using the FEM is larger than the laboratory results, the ultimate bearing capacity and settlements at high bearing pressures are acceptable.

After calibration of the FE model based on the laboratory tests for the unreinforced model, strip footing on reinforced sand was modeled. Zero-thickness and thin-layer interface elements were used in the model for pristine and cement-treated soil and geotextile interfaces, respectively.

Cement treatment produced cemented zones adhering to both sides of the geotextile. Inspections of the cement-treated geotextiles after the tests indicate that the cement-treated zone remained intact, which means that sliding between the sand and geotextile occurred at the interface between the cement-treated zone and sand. Therefore, in the FE model, a 1.5 mm thick interface zone was defined on both sides of the geotextile elements by thin layer interface elements. The average cement content of the treated zone was approximately 20%. The cohesion and internal friction angle of the cement-treated zone were determined to be 300 kPa and 38°, respectively.

The results of the numerical analysis of reinforced footings are shown in Fig. 15.

It can be seen in Fig. 15 that the results of the numerical model correlate well with the laboratory tests. Numerical calculations show that the cement treatment increased the bearing capacity of the reinforced footing by 10%, whereas based on the laboratory results it was improved by 12% for 30 cm geotextile with a cement-

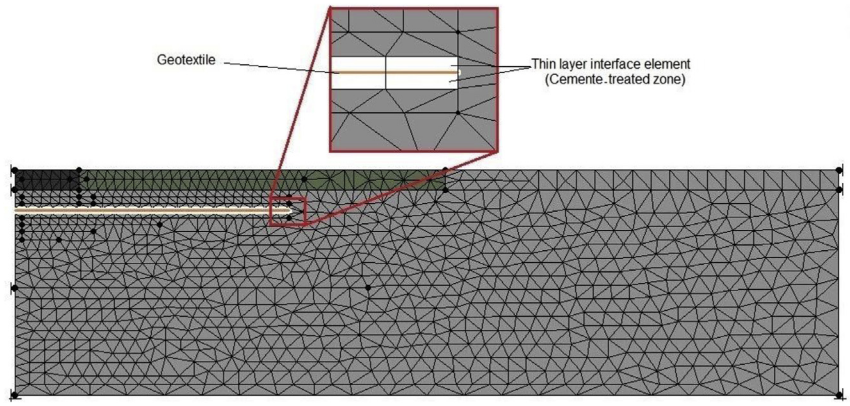

Fig. 13. Finite element model of the test setup.

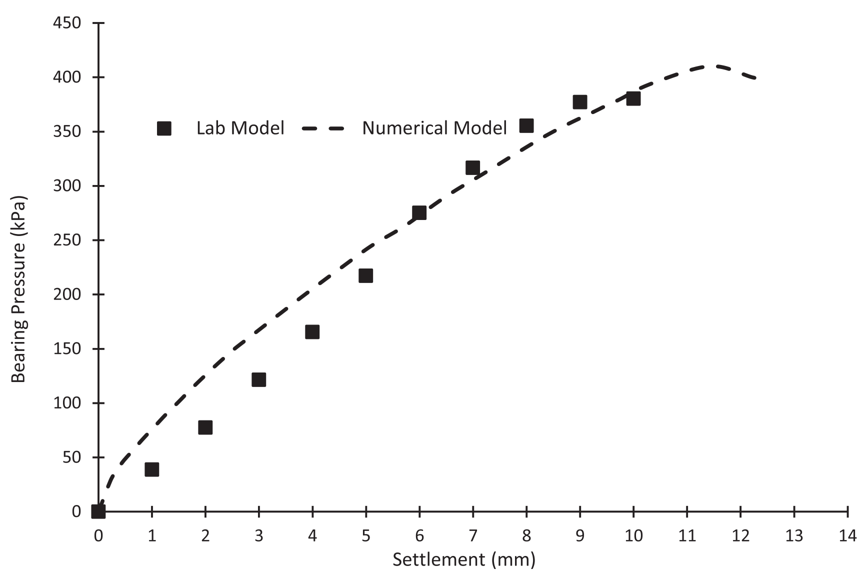

Fig. 14. Bearing capacity of unreinforced model based on laboratory testing and numerical analysis.

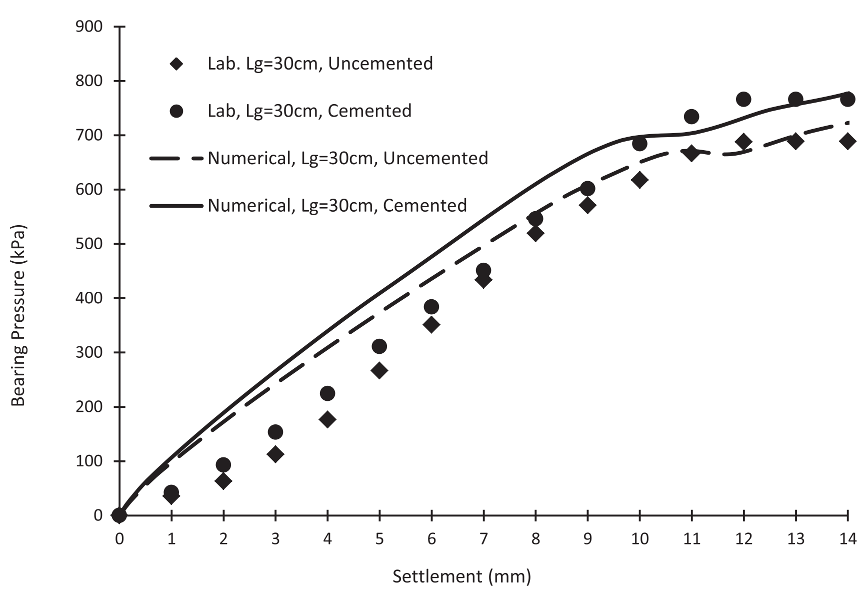

Fig. 15. Bearing capacity of reinforced model with and without cement-treated interface based on laboratory tests and numerical analysis (Lg = 30 cm).

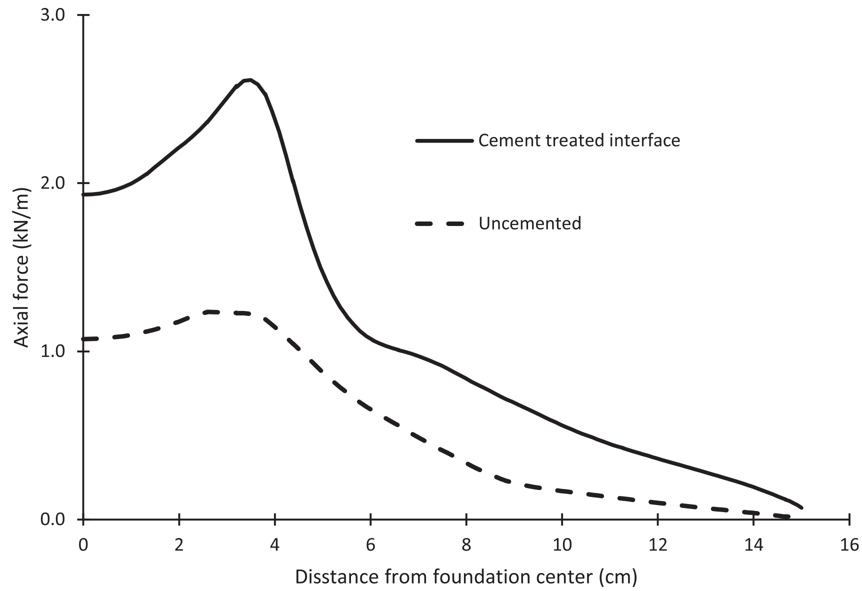

Fig. 16. Mobilized axial force of reinforcements (Lg = 30 cm).

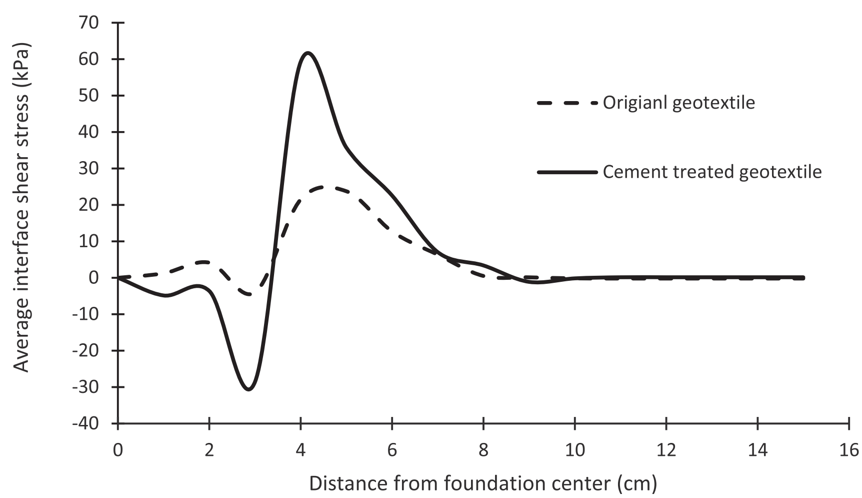

Fig. 17. Average mobilized interface shear stress (Lg = 30 cm).

treated interface.

The axial forces of the reinforcements based on the numerical analysis are shown in Fig. 16. As Fig. 16 shows, the mobilized axial force of the cement-treated geotextile was larger than the axial force of pristine geotextile. This can also be described based on the results in Fig. 17, which shows the average mobilized shear stress of the interface elements. The mobilized interface shear stress was increased in the cement-treated model, which means that, in the cement-treated model, the reinforcement sheet was restricted in the soil mass more strongly than in the pristine model, which resulted from the stronger interface parameters.

As shown in Fig. 5, the deformation of the geotextile sheet was localized near the edge of the foundation at up to 10 cm from the center. It can be seen in Figs. 16 and 17 that the mobilized axial load in the geotextile and the interface shear stress between the soil and geotextile are both also localized at the same location. The localized mobilization of the reinforcement forces depends on the failure mode of the soil (Patra and Shahu, 2012). No mobilized interface shear stress occurs in the last 5 cm of the geotextile from either side (the model is symmetric). Therefore, it can be concluded that only 20 cm of the central part of the geotextile had fully interacted with the surrounding soil and participated in the improvement in the bearing capacity. This is in accordance with the improvement in the bearing capacity shown in Fig. 10, in which the increment rate of improving ratio is shown to decrease as the length of the geotextile increases.

6. Conclusions

A series of laboratory tests were conducted to evaluate the effects of a cement-treated interface of sand and geotextile on the bearing capacity of strip footing on geotextile-reinforced sand. An FE model was developed to model the laboratory conditions and was applied to further studies after the calibration. The results of the laboratory tests showed that the bearing capacity of the footing on reinforced sand using a single layer of geotextile was 1.46- to 2.2-times the bearing capacity of the same footing on unreinforced sand, depending on the length of the geotextile. Treating the interface zone of the sand and geotextile of the same footing with 1.5 kg/m^2 of cement increased the bearing capacity by 1.71- to 2.34-times that found under unreinforced conditions. The effects of cement treatment on the improvement of the bearing capacity was approximately 17% for Lg/B = 2.6 and 6% for Lg/B = 12 depending on the length of the geotextile. This means that the effectiveness of the cement treatment of the interface zone on the bearing capacity is more evident for shorter reinforcements with a shorter anchorage length. The bearing capacity of geocell- or geogrid-reinforced footings is 10–15% more than the bearing capacity of the same footings reinforced using geotextile. Therefore, geotextile with a cement-treated interface can be considered an alternative for geocell and geogrid reinforcements in areas where cement is plentiful and cheap. In addition, the rate of improvement in the bearing pressure of cement-treated geotextile-reinforced models was more evident in smaller settlements when compared to pristine geotextile-reinforced models. This means that cement treatment of the interface zone can be used to reduce the settlement of footings on geotextile-reinforced sand. Cement treatment of the interface zone reduces the required anchorage length. The results of laboratory tests indicate that, for an equal ultimate bearing capacity, the required anchorage length of cement-treated geotextiles was approximately 60% of the required anchorage length of pristine geotextiles. The durability of cement-treated geotextile was not investigated in this study. Further research is required to determine the corrosive effect of cement on geotextile.

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