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

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ABSTRACT

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