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# Laboratory Modeling of a Spread Footing on Sand Reinforced by Strips of Carbon Fiber Reinforcement

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**ABSTRACT:**

The bearing capacity of a square footing on sand reinforced by carbon fiber reinforced polymer (CFRP) was investigated in the laboratory. A sand box with dimensions of 100×100×90cm was utilized as the test bed for experiments. A 20×20×2cm steel plate was employed to simulate the square footing. The sand was reinforced using 2cm width carbon fiber reinforced polymer (CFRP) strips with different numbers of strips, lengths, and depths. The effect of the horizontal distances between CFRP strips and chemical treatment of the interface of the CFRP and sand on the bearing capacity of the footing were investigated. The results of these tests indicated that with the same number of reinforcement strips, placing the reinforcement strips close to the center of the footing increases the bearing capacity of the foundation. The bearing capacity of the foundation on sand reinforced with a single layer CFRP strips could be improved by 50% in optimal condition. Epoxy resin treatment of the interface of the sand and CFRP strips increased the bearing capacity of the foundation by an additional 11%.

**KEYWORDS:**

Carbon fiber reinforcement strips, Reinforced soil, Bearing capacity, Spread footing.

## 1. Introduction

The bearing capacity of foundations depends on the mechanical properties of the underlying soil, shape, size, and depth of the foundation, and the loading condition. Friction, cohesion, interlocking, and confinement are effective parameters on the shear strength of the soil as a granular material. Chemical and mechanical methods could be used to improve the mechanical properties of the soil. Geosynthetics inclusion within a soil mass could be employed to improve the mechanical characteristics of the soil as a mechanical stabilization method (Shukla and Yin 2006; Yang et al. 2016). Mechanical stabilizers are generally used to improve the shear strength of soil, stability and performance of Slopes, pavements, foundations and fills (Chen et al. 2018; Goodarzi and Shahnazari 2019; Ouria and Mahmoudi 2018; Xu et al. 2019). The stability or bearing capacity of geosynthetic-reinforced soil systems depends on three criteria, namely: pull-out, tensile failure, and the relative slippage of the reinforcements in the soil (Fan et al. 2019).

Geosynthetics are essential elements for sustainable development (Dixon et al. 2017). In the design and construction of reinforced soil structures, the optimal use of reinforcements is a key point. The total cost of the construction is more than four or five times the cost of the geosynthetics itself (Ouria et al. 2016). In addition, the cost of earthworks, including excavation, placement of reinforcements, backfill, and compaction, is directly proportional to the length of the reinforcements and the number of layers. The additional number of reinforcement layers could be used to increases the bearing capacity of the foundation until a limited level (Basudhar et al. 2007; Chen and Abu-Farsakh 2015; Tafreshi and Dawson 2010).

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The effectiveness of the additional reinforcement layers in settlement reduction was not reported in previous researches (Basudhar et al. 2007). The bearing capacity of the foundation could be increased up to a limited level by increasing the length of reinforcements (Cicek et al. 2015; Ouria et al. 2020). Based on the experimental results, 3 to 6 times the foundation width was proposed for the optimum length of the reinforcement elements to achieve the maximum bearing capacity (Abu-Farsakh et al. 2013; Cicek et al. 2015). Optimal embedment depths of the last and first layers of geosynthetic reinforcement are approximately 1.25- and 0.33-0.5- times the width of the foundation, respectively (Abu-Farsakh et al. 2013; Chakraborty and Kumar 2015). The shape and the material of the geosynthetics are also effective factors on the bearing capacity of the foundation (Hegde and Sitharam 2015; Oliaei and Kouzegaran 2017). Reinforcing of the soil under the foundation with one layer of geogrid reinforcement could improve the ultimate bearing capacity by 10-15% more than a one-layer non-oven geotextile reinforcement (Guido et al. 1986; Tafreshi and Dawson 2010).

In order to improve the ultimate bearing capacity of a foundation on a reinforced soil, increasing the length of the reinforcement is not occasionally a reasonable choice (Ouria et al. 2020). Chemical bonding or mechanical anchorage could be employed to improve the friction, adhesion, and interlocking of the soil and geosynthetic, consequently improving the bearing capacity of the reinforced soil (Aria et al. 2019; Mosallanezhad et al. 2016; Ouria et al. 2021; Ouria and Heidarly 2021; Ouria and Mahmoudi 2018; Ouria and Sadeghpour 2022; Xu et al. 2018). Although geotextiles are widely used in geotechnical projects, there are several problems such as low modulus of elasticity, susceptibility to the aggressive environment, and the creep associated with them (Ouria et al. 2016; Toufigh et al. 2014a). Therefore, using high strength and durable synthetic materials in mechanically stabilized soil systems could be reasonable both from economical and design aspects to solve these problems. The high tensile strength of carbon fiber reinforcements (CFR) makes it an ideal material for being used as a reinforcement element within the soil mass to address its weak tensile capacity and increase the confinement. CFR is widely used in structure reinforcement and retrofitting (Toufigh et al. 2014b).

The CFR improved soil is a nonhomogeneous material with a distinctive interface region between the soil and the CFR sheets. Therefore, the mechanical properties of the improved soil are dependent on the quality of the interface behavior between these two materials. The interface behavior of soil and CFR is also affected by the epoxy resin and its construction and curing methods (Toufigh et al. 2016). Ouria et al. (2016) studied the behavior of a CFR reinforced retaining wall by finite elements method. They concluded that using high strength CFR reinforcements in retaining walls could result in an effectively reduced number of reinforcement's layers if enough pull-out capacity for CFR sheets provided. In order to employ the high tensile strength of CFR sheets as a reinforcement for soil, it is essential to provide the required pull-out capacity. The pull-out strength of geosynthetic reinforcements depends on the interface friction angle, adhesion, normal stress level, and anchorage length. Treatment of the interface of the geosynthetic and soil could be employed to improve the pullout resistance of the geosynthetic in soil (Ouria et al. 2019, 2021; Ouria and Mahmoudi 2018).

Hong et al. (2014) and Toufigh et al. (2014b) investigated the pull-out behavior of glass fiber reinforcement (GFR) and CFR reinforcement with sand under low normal stress. Based on their results, GFR reinforcement has a more progressive pull-out than CFR reinforcement. Toufigh et al. (2016) suggested epoxy resin treatment of the interface of CFR and sand to improve their interface properties.

In this research, the bearing capacity of a square spread footing on sand reinforced by CFR was investigated in the laboratory. Since the tensile strength of CFR is much higher than the ordinary geosynthetics, and also based on the results of previous experiments (Ouria et al. 2020; Ouria and Sadeghpour, 2022) the sand was reinforced by discrete strips of CFR strips to optimize the amount of the used CFR. In order to provide enough anchorage length for CFR sheets to utilize their high tensile capacity, both chemical and mechanical methods of interface treatment were employed. Epoxy resin was used to bond sand particles to the CFR surface to improve its roughness and increase their pull-out capacity and the bearing capacity of the footing.

## 2. Materials and methods

### 2.1. Sand

The sand used in the laboratory was collected from Ardabil city located in the northwest of Iran. It was classified as poorly graded sand (SP) in the unified soil classification system based on ASTM D2487-11 (ASTM D2487-11 2011). The direct shear test according to ASTM D3080-04 (ASTM D3080-11 2011) was used to determine its internal friction angle. The unit weight and moisture content of the sand were determined based on ASTM C127-07 (ASTM C127-07 2007) and ASTM D2216-05 (ASTM D2216-10 2010) respectively. The grain size distribution curve and basic characteristics of the sand are given in Fig. 1 and Table 1 respectively.

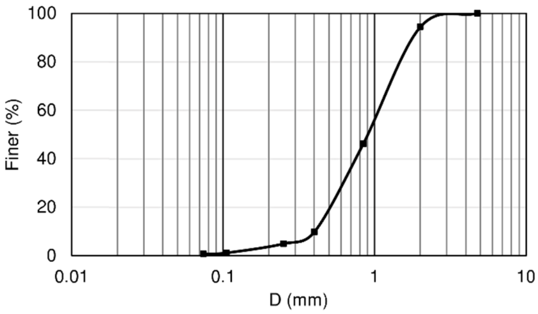


**Fig. 1.** Grain size distribution of the sand material used in this study

**Table 1.** Basic parameters of the sand used in this study

| $D_{10}$ | $D_{30}$ | $D_{60}$ | $w$ | $\gamma$ | $\varphi$ | $e$ |
|---|---|---|---|---|---|---|
| 0.4mm | 0.6mm | 1.2mm | 2% | 16.8kN/m$^3$ | 39° | 0.51 |

## 2.2. Carbon fiber reinforcement (CFR)

Unidirectional CFR sheets were used in this study as reinforcement elements. The tensile tests were performed according to ASTM D3039 (ASTM D3039 2017) on CFRP sheets. The thickness of CFR sheets was 1mm. The average tensile strength, modulus of elasticity, and the Poisson's ratio were determined as 426.5MPa, 42.44GPa, and 0.34, respectively.

## 2.3. Epoxy resin

Carbon fiber reinforcements are commonly used in construction and retrofitting of structural elements in reinforced concrete structures where the epoxy resin is used to form a solid shape or adhere the reinforcement to other structural elements (Toufigh et al. 2016). In this study, the epoxy resin was used to adhere the sand particle to the surface of CFRP in order to provide a rough surface with a high friction angle. The epoxy used in this study was made of three parts of resin and one hardener by volume. The epoxy had a pot life of 2 h at room temperature and was fully cured for 24 hours at 25°C.

## 2.4. Experimental setup

A steel box with dimensions of 100cm (length)× 70cm (height)×100cm (width) was used as the test base. It was made of a 6-mm steel plate and reinforced by two steel frames around its perimeter to assure its lateral rigidity and prevent from lateral expansion. A 200kN hydraulic jack, with a manual loading mechanism welded to the box frame, was used as the loading device. Measurement devices, including an LVDT and a displacement transducer, were used to record the test data. A steel plate was used as the spread footing. Its length, width, and thickness were 20, 20, and 2.5cm, respectively. Fig. 2 shows the schematic of the test box, the loading device, and the photograph of the test setup.

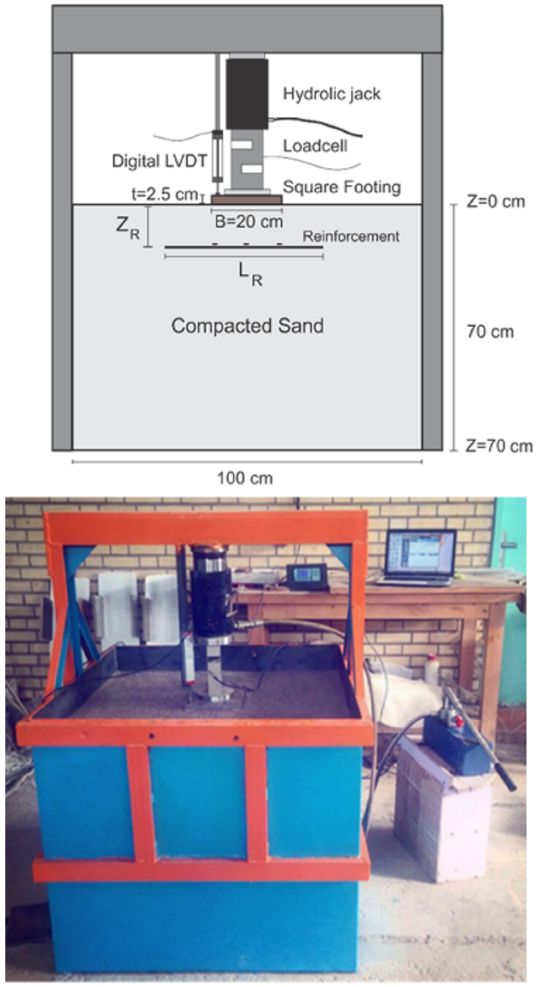


**Fig. 2.** Schematic and photograph of the test setup

## 2.5. Test program

Carbon fiber polymer is stronger and more expensive than other geosynthetics such as geotextiles and geogrids. Therefore, the optimal use of these reinforcements has great importance both from engineering and economical views. In this study, strips of carbon fiber polymer with 2cm width were used to reinforce the sand. The effective parameters on the bearing capacity of spread footing on reinforced sand, including embedment depth of reinforcements, length of reinforcements, and distance between reinforcement strips, were investigated. Also, the effect of epoxy resin treatment of the interface of the sand and CFRP strips on the bearing capacity of the foundation were studied.

All the tests were conducted with a single layer of reinforcement strips. The effect of the embedment depth of the reinforcements on the bearing capacity of the spread footing was studied with four different embedment depths, including 5, 7.5, 10, and 15cm. After the determination of the most effective embedment depth of reinforcements on the bearing capacity, the effect of the reinforcement length was studied with ten different lengths, namely 5, 7.5, 10, 15, 20, 25, 30, 40, 50, and 60cm. The effect of the horizontal distance between reinforcement strips on the bearing capacity of foundation on the reinforced soil was studied with three different distances, including 3, 6, and 9cm or 2, 10, and 18cm for configurations with 6 or 4 strips of reinforcements, respectively as shown in Fig. 3. The reinforcement configuration with the maximum bearing capacity resulted from simple run-out reinforcements was selected to investigate the effect of interface treatment by epoxy resin on the bearing capacity of the footing.

### *2.6. Preparation and test procedure*

The sand was placed in the test tank using the raining technique. In each test, to maintain the compactness and unit weight of the sand in test models, the average unit weight of the sand kept constant as a control criterion (Ouria and Mahmoudi 2018). The average unit weight of the sand used in this study was 16.8KN/m3. In each test, 1176kg of the sand with a height of 70cm in the box was used. The sand was placed in seven layers in the box and the height and the weight of each layer was 10cm and 168kG for unreinforced models. In the preparation of reinforced models, where a reinforcement layer was required to embed within the last top soil layer. Therefore, the top soil layer was constructed in two stages to reach the final height of 70cm. For compacting of each layer, a flat steel hammer with 12kg weight and dimensions of 25cm×50cm was used. The hammer was dropped 48 times from a height of 12cm in eight different locations. In order to achieve a uniform compaction and prevent from over-compaction of sand layers in particular locations, a template consisting of eight equal areas was used. The preparation procedure of laboratory models is shown in Fig. 4. Models included epoxy resin treated reinforcements, cured at the laboratory temperature about 25 degrees Celsius for 24 hours after preparation and then loaded. Since the loading mechanism was a manual hydraulic jack, the pumping handle was moved with a rate of two seconds per cycle with a loading rate of 1 mm per minute approximately. In order to assure the repeatability of the tests, all tests repeated reaped at least 3 times and the statistical average was considered as the final result.

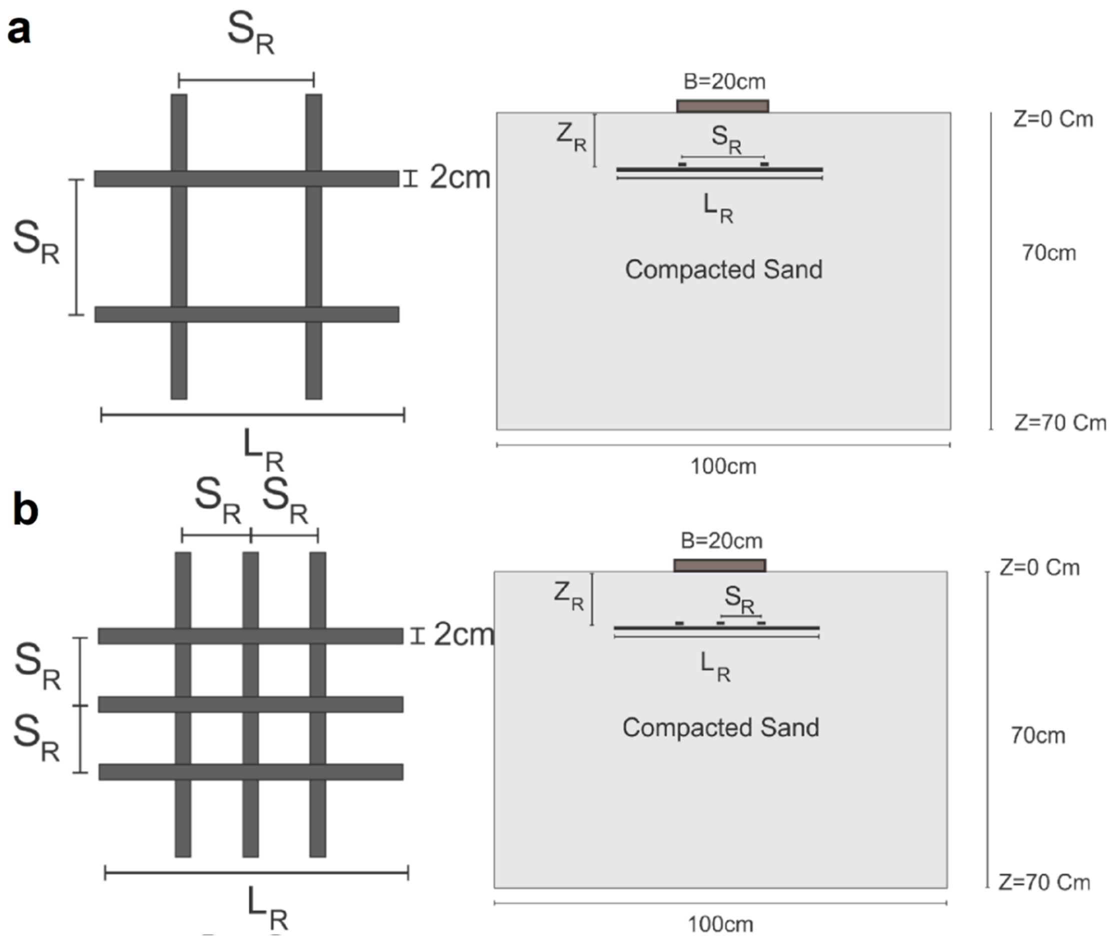


**Fig. 3**. The layout of the reinforcement's configuration: **a)** 4 strips of CFRP, **b)** 6 strips of CFRP

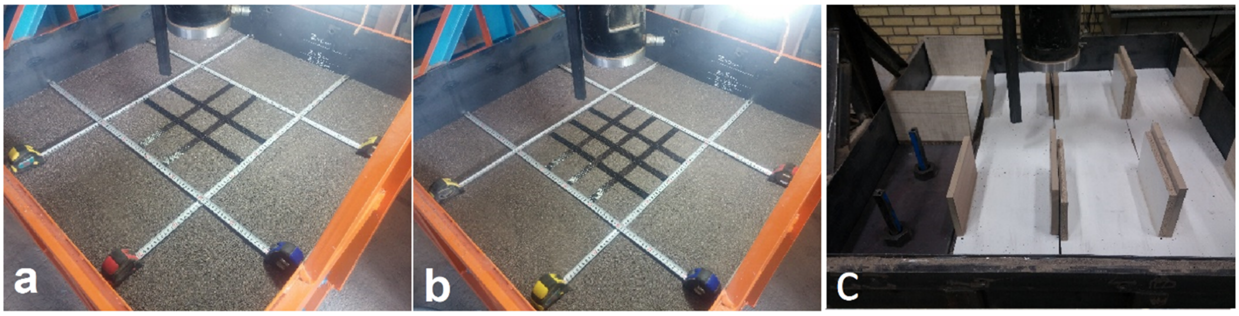


**Fig. 4.** Preparation of specimens reinforced with: **a)** 4 strips of CFRP, **b)** 6 strips of CFRP, **c)** compaction

### *2.7. Scale effect*

The results of a small-scale laboratory model should be properly related to the results of large-scale prototype. Using the Buckingham-π theorem, the dimensionless bearing capacity of a spread footing on reinforced soil could be expressed as (Dixit and Mandal 1993) (Wood 2004):

$$\frac{q_u}{B.\gamma} = f\left(\varphi, \delta, \frac{D_f}{B}, \frac{R_t}{B\gamma}, \frac{b}{B}, \frac{Z_R}{B}, \frac{L_R}{B}\right) \tag{1}$$

Where $q_u$, $B$, and $D_f$ are the ultimate bearing capacity, widths, and the depths of the footing, $\gamma$ and $\varphi$ are the unit weight and the internal friction angle of the soil, $\delta$ is the interface friction angle of the soil and the CFRP, $R_t$, $b$, $Z_R$ and $L_R$ are the tensile strength, cross sectional width, and the buried depth of the CFR strips respectively.

The stress-strain behavior of the soil is nonlinear and depends on the initial confining pressure and the void ratio. Therefore, there must be a compatibility between the initial void ratios and the stress levels in the model and the prototype in addition to the dimensional similarity (Altaee and Fellenius 1994).

## 3. Results

The failure mode of sand and the disruption of reinforcements under the spread footing are shown in Figs. 5-a, and 5-b, respectively. The disruption of the reinforcements occurred under the edge of the footing. Therefore, it can be realized that the CFR strips have contributed in the bearing capacity of the footing.

The results of laboratory tests conducted for models with 4 and 6 strips of reinforcements, with the length of 40cm for each strip and depth of reinforcement $Z_R$=7.5cm ($Z_R/B$=0.75) with different horizontal distances of reinforcement strips are illustrated in a dimensionless form in Fig. 6. $q/(B.\gamma)$ is the dimensionless bearing capacity of the footing and S/B is the ratio of settlement per widths of the footing. As can be seen in Fig. 6 the bearing capacity of the footing depends on the $S_R$, that is the horizontal distance between CFR strips.

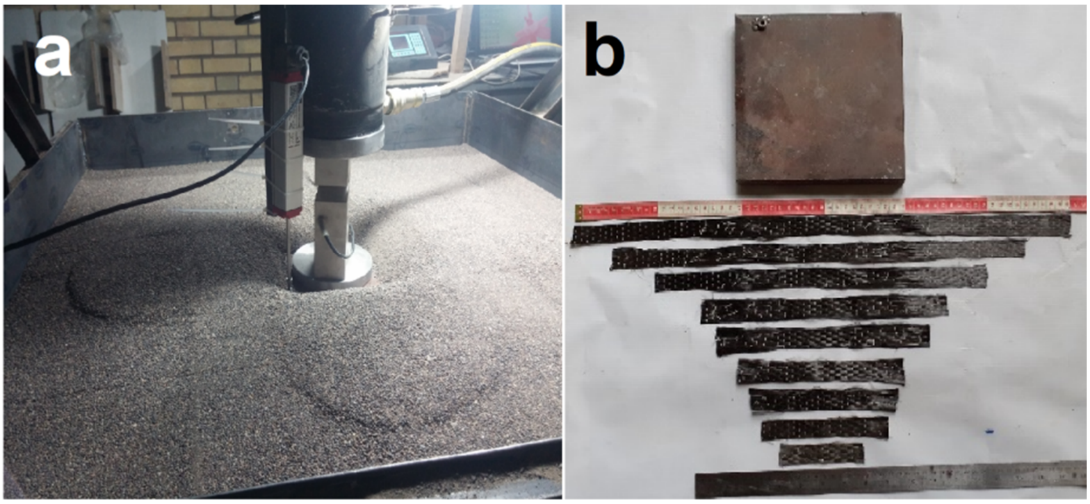


**Fig. 5. a)** The failure of soil under loaded spread footing, **b)** disruption of CFRP strips under the footing

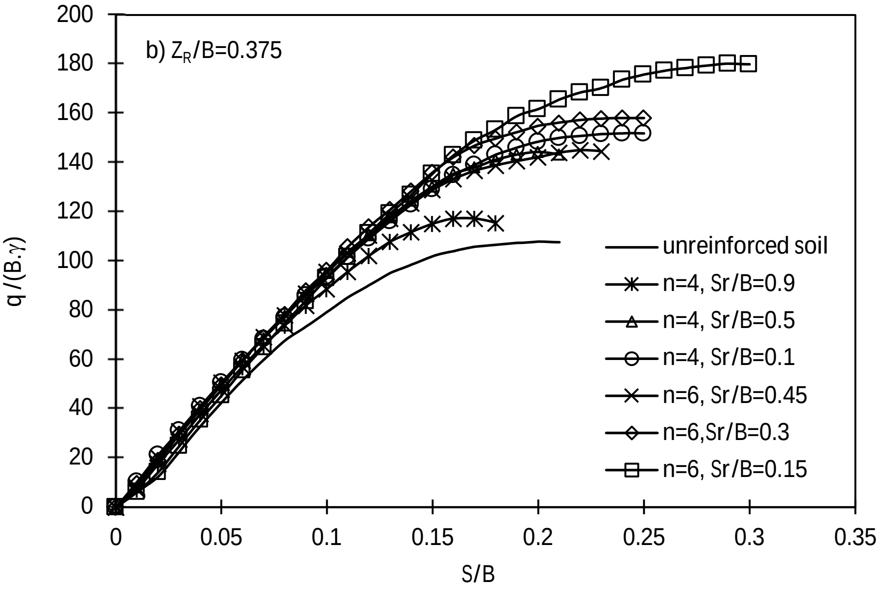


**Fig. 6.** Results of laboratory test with 4 and 6 strips of 40cm long reinforcements with $Z_R/B$=0.375 and different values of S/B

Similar tests were conducted with different depths of reinforcements and the results were summarized in Fig. 7. It can be seen in Fig. 7 that the dimensionless ultimate bearing capacity ($q_u/B.\gamma$) of the foundation was increased as the depth of the reinforcement was increased, and then it was decreased. The maximum bearing capacity was achieved when the embedment depth of the reinforcements was 7.5cm ($Z_R/B$=0.375) for both 4 and 6 strips models. As shown in Fig. 7, the effect of the horizontal distances of the reinforcement strips ($S_R$) on the ultimate bearing capacity is more evident in shallow depths of reinforcements. At each embedment depths, the maximum bearing capacity was achieved when the CFR reinforcement strips were placed under the center of the footing. Based on the results of tests conducted with different embedment depths of reinforcements, the number of reinforcement strips and their horizontal distances, the maximum bearing capacity of the foundation was achieved for the model with 6 strips of reinforcement embedded at the depths ($Z_R$) of 7.5cm ($Z_R/B$=0.75) with horizontal distances ($S_R$) of 3cm ($S_R/B$=0.15). This configuration was used for further investigation on the effect of the reinforcement length on the ultimate bearing capacity of the foundation.

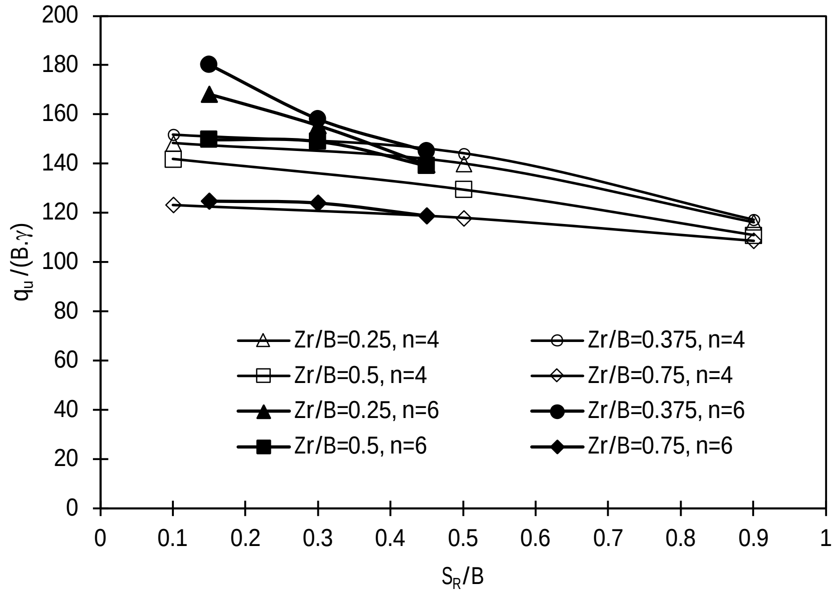


**Fig. 7.** Effect of the horizontal distance of reinforcement strips on ultimate bearing capacity in different depths

To investigate the effect of the length of CFR strips on the bearing capacity of the foundation, tests were conducted on ten different lengths of CFR strips, including 5, 10, 15, 17.5, 20, 25, 30, 40, 50 and 60cm ($LR/B$=0.25-3), for the test model reinforced with 6 CFR strips with 3cm horizontal distance between strips ($Sr$) and embedding depth ($Zr$) of 7.5cm. Fig. 8 shows the results of these test conducted on models reinforced with different lengths of CFR strips. It can be seen in Fig. 8 that the bearing capacity was increased as the reinforcement length increases but at a decreasing rate and was achieved to a certain level after approximately 40cm ($L_R/B$=2). The disruptions of reinforcements with different lengths that were shown in Fig. 5b have occurred under the edges of the foundation. The disruption of reinforcements is the result of their intersection with the failure surface of the soil. It can be seen in Fig. 8 that the reinforcements with the length of 0.5B (10cm) and longer were disrupted and consequently increased the bearing capacity of the foundation.

The bearing pressure ratio (BPR) is the bearing pressure of the reinforced soil under the footing at a certain settlement divided by the bearing pressure of the unreinforced soil under the footing at the same settlement level. BPR for test models, reinforced with different lengths of reinforcements, is illustrated in Fig. 9. The BPR is the ratio of the bearing pressure of the reinforced model to that of the unreinforced model at the same settlement. As can be seen in Fig. 9, the effect of the usage of CFR strips as reinforcement elements on improving the bearing pressure ratio is more evident at lower settlements as well as higher settlements. The maximum improvement of the BPR for all reinforced models was achieved at $S/B$=0.3 approximately, while it was 0.2 for the unreinforced model. Also, at very low settlement ratio of 0.02 a considerable improvement of the bearing capacity ratio was observed for all test models.

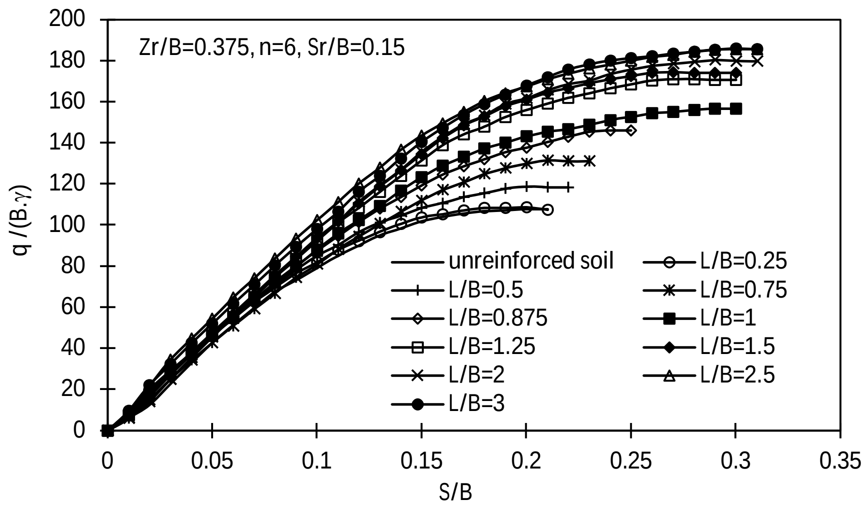


**Fig. 8.** Results of laboratory test using 6 strips of CFRP with different lengths

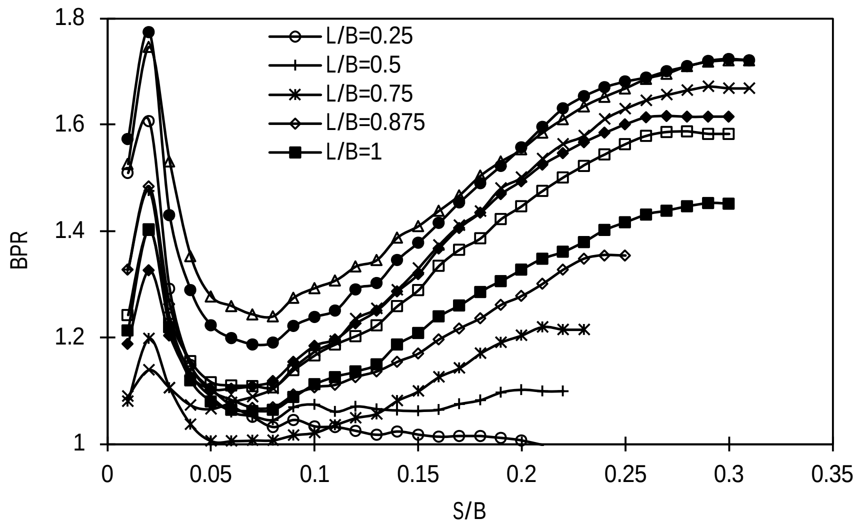


**Fig. 9.** BPR for spread footings on sand reinforced with different lengths of CFRP strips

Chemical and mechanical treatment of the interface of the soil and the reinforcement could be employed to improve the bearing capacity of footing in more effective ways. In this study the epoxy resin was used to improve the interface properties of sand and the CFR strips. Fig. 10 shows the results of tests conducted on models with epoxy resin treated interfaces. A comparison of the Figs. 10 and 8 shows that the epoxy resin treatment of the interface of the CFR and sand has improved the bearing capacity and the load-settlement behavior of the foundation. The BPR of models with epoxy resin treated interface is shown in Fig. 11. It can be seen in this figure that the BPR has increased as the settlement increased until *S/B*= 0.35 approximately. Therefore, it can be inferred that epoxy resin treatment of the interface of the CFRP and the sand fortifies the hardening character of the load-displacement curve of the footing. Also at the same settlement level, the models with epoxy resin treated interface showed higher bearing pressure. Therefore, resin treatment of the interface of the CFR and sand reduces the settlement of the footing.

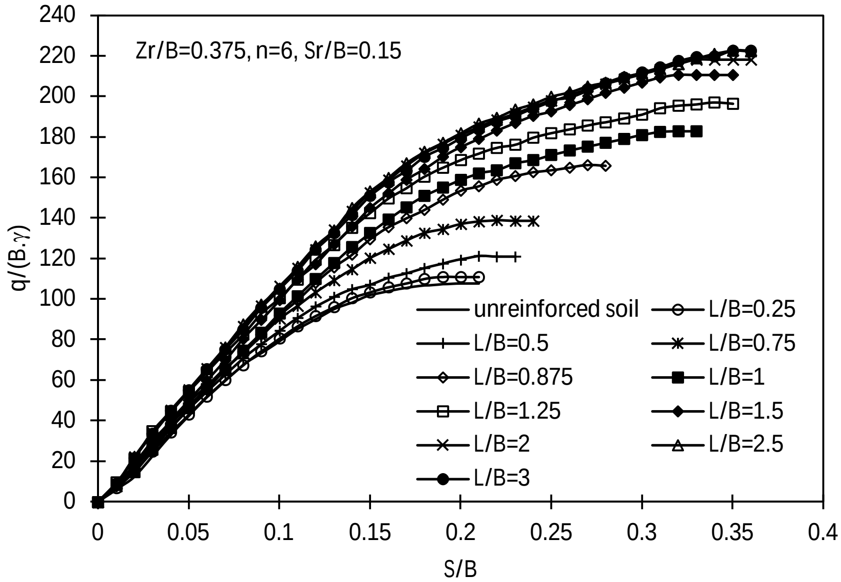


**Fig. 10.** Results of laboratory test on reinforced sand with different lengths of CFRP strips with epoxy resin treated interface

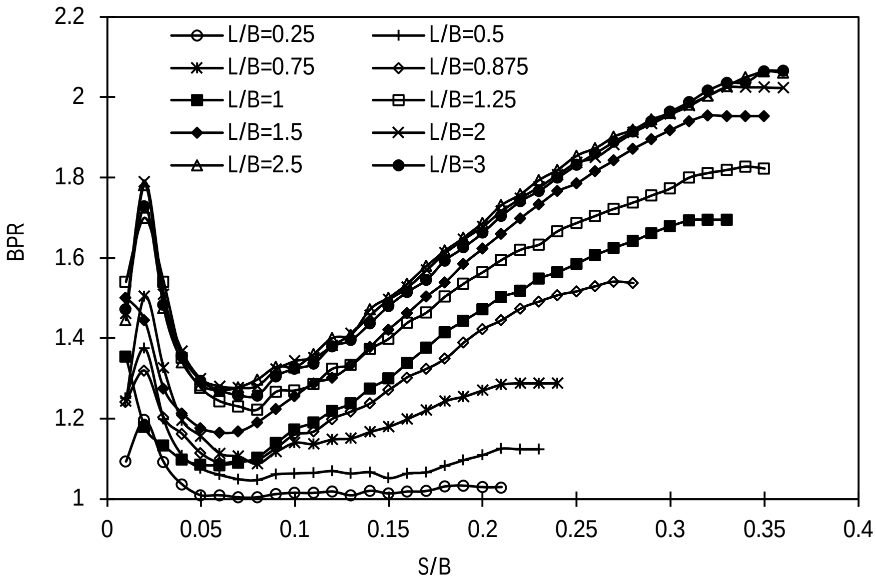


**Fig. 11.** Relative bearing pressure of spread footing on CFRP reinforced sand with epoxy resin treated interface

The final results of the ultimate bearing pressure (UBPR) for reinforced models with and without epoxy resin treatment are illustrated in Fig. 12 for *S/B*=0.2 as well as the ultimate state. In this figure, ERCFR denotes CFR with epoxy resin treated interface. The ultimate state of bearing pressure shown in this figure is the ratio of the bearing pressure of reinforced model to that of the unreinforced model at *S/B*=0.3 and *S/B*=0.35 for reinforced models with and without epoxy resin treated interface respectively. The bearing capacity of the foundation reinforced with 40cm length reinforcement strips (*LR/B*=2) was increased by approximately 50% for ordinary reinforcement 68% for reinforcement with epoxy resin treated interface at *S/B*=0.2. It was increased by 67% for ordinary reinforcement and 102% for reinforcement with epoxy resin treated interface at the ultimate state. Roy and Deb (Roy and Deb 2017) reported a 40% improvement in the bearing capacity of a 7.5cm×7.5cm square footing on a granular fill on soft soil reinforced with a single layer 30cm×30cm continuous reinforcement located at an embedment depth similar to that in this study. Abu-Farsakh et al. (Abu-Farsakh et al. 2013) reported a 30-40% improvement in the bearing capacity of a 15.2cm×15.2cm square footing on a 147cm×86cm single layer reinforcement depending on the material of the reinforcement. In this study, the ratio of the total area of 6 reinforcement strips with length of 40cm to the area of the square footing was 1.2 while it was 54 for single layer reinforcement model reported by Abu-Farsakh et al. (Abu-Farsakh et al. 2013) and 16 for single layer reinforced model reported by Roy and Deb (Roy and Deb 2017). Considering the volume of the material used as the reinforcement, (L/B=2) CFR with epoxy resin treated interface could be used as an effective material in reinforced soil systems.

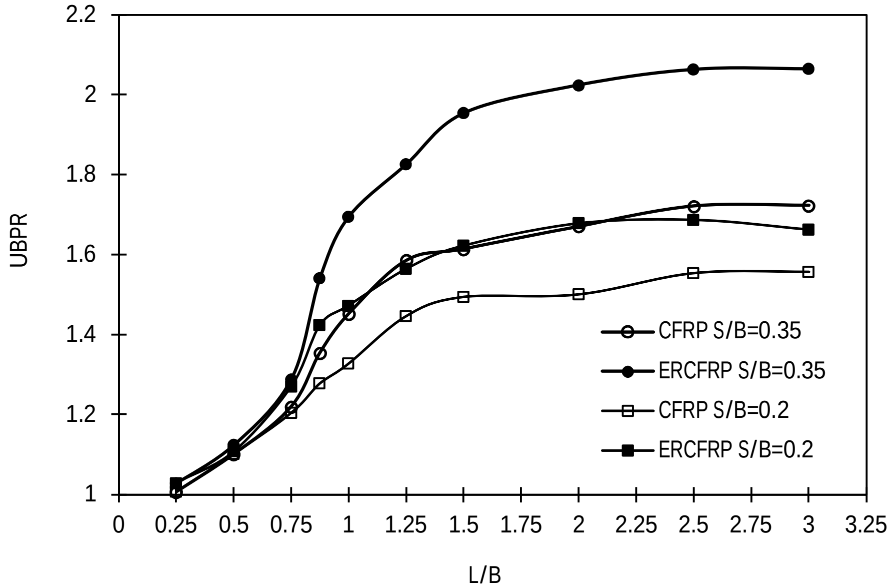


**Fig. 12.** Comparing the effect of the epoxy resin treatment of the sand-CFR interface on the ultimate bearing capacity ratio of the foundation

## Conclusions

In this research, a series of laboratory tests were conducted to evaluate the possibility of the application of strips of carbon fiber reinforcement as a reinforcement material to improve the bearing capacity of a 20cm×20cm square footing on the sand. Since the tensile strength of the CFR sheet is very high, it was used in the form of 2cm width strips. Method of epoxy resin treatment of the interface of the CFR sheet and sand as a chemical method was used to improve the pull-out capacity of CFR sheets and therefore the bearing capacity of the footing. The tests conducted with different reinforcement lengths including lengths shorter than the foundation width.

- The results of the laboratory tests showed that short length reinforcements could participate in the bearing capacity improvement if the reinforcement sheet be long enough to intersect the failure surface.
- With the same number of reinforcement strips, locating the reinforcements close to the center of the footing, increases the effectiveness of the reinforcements on bearing capacity of the foundation.
- The optimum length of the reinforcement strips is 2 times the foundation width for CFR strips while it was reported to be 3-6 times the foundation width for the geotextile and geo-grid reinforcements.

- A single-layer of CFR strips increased the bearing capacity of the foundation for $S/B$=0.2 at least by 50% for pristine CFRP and 67% for CFRP with epoxy resin treated interface that is much more than the improvements reported for geotextile and geo-grid reinforcements with longer lengths of reinforcements.

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