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Analysis of Settlement Profiles of Shallow Strip Footings Resting on Geosynthetic-Reinforced Sands

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Abstract: The present study involves the development of a small-scale physical model for analyzing the settlement profiles under shallow strip footing resting on geosynthetic reinforced sands. Air-dried sand with an average particle size (D_{50}) of 0.48 mm was used as the model soil. The selection of model reinforcement was made by adopting scaling laws linking the tensile strength characteristics of model geosynthetic to that of commercial prototypes. A series of experiments were performed by pluviating sand at a relative density of 90%, and by varying the number and spacing between the subsequent reinforcing layers. The tests were performed under displacement-controlled conditions, and instrumented using a load cell and linearly variable displacement transducer (LVDT). The front side of the container was made of a perspex sheet to aid in the particle image velocimetry (PIV) technique. The results were interpreted by plotting the load-displacement curve and the displacement vectors obtained through PIV analysis. The reinforcement inclusion was observed as effective in controlling the heaving of the foundation and overall soil settlement. From the displacement vectors, the load-dispersion angle was observed to be in the range of 20° to 30°, and was found to increase with higher reinforcement layers.

Keywords: *Geosynthetics, Settlement, Strip footings, GeoPIV, Displacement Vectors*

1 Introduction

The vertical and horizontal stresses from the superstructure on the footings may cause foundation soil failures and excessive settlements detrimental to the overlying structure. Considering the preceding, numerous ground improvement procedures have been developed, and soil reinforcement has been extensively praised for its versatility in technical, economic, and environmental feasibility and ease of use in many incarnations. Soil reinforcements, starting with metallic strip reinforcements [1, 2], broadened their domain with sheet type reinforcements, and finally, revolutionary geosynthetics in various forms have superseded them all. Geosynthetic has been successfully adopted as a cost effective solution to improve the bearing capacity and prevent soil settlement beneath the foundation. Researchers have conducted an increasing number of studies on the subject in the last few years [3, 4, 5]. The role of geosynthetic material are diverse, as it can serve multiple purposes of reinforcement, separation, filtration, drainage, containment, and confinement of soil.

One such viable utility involves placement of high tensile strength reinforcing members under the footing for increasing the ultimate bearing capacity of sandy deposits [1, 6, 7]. A ground-breaking study was conducted to this effect [8] on the influence of reinforcing layers placed under a foundation on the bearing capacity of sandy soil underlain by soft clay. Placement of a low-stiffness polymer net under the footing was observed to increase the bearing capacity of the soft soil significantly. Addition of geosynthetic reinforcement to the soil provides the soil with more lateral constraint, which may enhance the load spread angle and decrease the bearing pressures. Generally, the load transfer in soil occurs through grain-to-grain contact. For the sand grains below the footing, each grain transfers the load to the grain below it. To spread the load over a larger area, the entire soil layer in the reinforced soil layer behaves like a semi-rigid slab. There is a lot of friction generated at the interface of soil and geosynthetic layer to confine the soil. A geosynthetic layer, as compared to an unreinforced soil, aids in spreading the applied surface load across a wider area by providing a restraint for the granular fill. As per traditional method, a load dispersion ratio of 2:1 (vertical: horizontal) is generally assumed beyond the edges of the surface-loaded zone, and this assumption is used to estimate the vertical stresses in the foundation soil empirically.

The pressure is transferred from below the footing base of width "B" to the underlying soil layer and redistributed over a wide width of "$B+\Delta B$" by the geosynthetic, thereby reducing the intensity of the pressure and increasing the bearing capacity. Due to the semi-rigid nature of the geosynthetic reinforced foundation, the additional load dispersion width "ΔB" in a reinforced section is greater than that in an unreinforced section. In order to gain further insight into this phenomena, a series of small-scale physical model tests were carried out under displacement-controlled conditions to investigate the settlement reduction and dispersion of a load under a strip footing resting on geosynthetic reinforced sand deposits. In order to comprehend and interpret accurately the load dispersion mechanism of geosynthetic reinforced foundation, Particle Image Velocimetry (PIV) technique [9] has been employed, as explained in subsequent sections.

2 Materials

2.1 Sand and Geosynthetic

The air dried fine sand used below the model strip footing in the present analysis has an average particle size (D_{50}) of 0.48 mm. Figure 1 represents the grain size distribution of the sand used in the experiment. Geotechnical investigations were conducted on the sand as per BIS specifications, including sieve analyses, specific gravity tests, maximum and minimum density tests, and direct shear testing. Table 1 summarizes the engineering properties of dry sand. The maximum and minimum dry densities were found to be 17.27 kN/m^3 and 15.23 kN/m^3 respectively. The sand was densely packed into the model tank during subsequent investigations, resulting in a density of 17.04 kN/m^3 (D_r = 90%). The sand pluviation method was used to obtain specific relative densities, which is reportedly an excellent way to make uniform and homogeneous sand beds with a given relative density [10, 11]. In this investigation, a sand pluviation hopper was employed to release sand into the container from a predetermined height to achieve a defined average relative density. The desired height was determined from the calibrated graph shown in Figure 2. Direct shear tests conducted on a typical shear box (60 mm x 60 mm x 20 mm) by pluvaiting the sand sample in layers revealed the angle of internal friction of the sand as about 32.5°. Additionally, the friction coefficient between sand and reinforcement was determined from a conventional direct shear test apparatus and observed to be 0.997 [Table 2].

During testing of model footing, a woven polypropylene geotextile was used as the reinforcing geosynthetic. The tensile strength of the geotextile is 0.025 kN/m and 0.0625 kN/m at 2% strain and 5% strain, respectively. While the strength of this geosynthetics would be regarded as low in a full-scale application, considering appropriate scaling laws linking the full-scale prototype and the corresponding model, it replicates a highly tensile model reinforcement. The interface friction angle for woven polypropylene geotextile in a direct shear box is evaluated as 32.4°. Table 2 summarizes the basic properties of the geosynthetics used in the experiment. Figure 3 depicts the load-elongation behaviour of the model geosynthetic as evaluated from standard wide-width tensile strength tests, as per ASTM D4595-17.

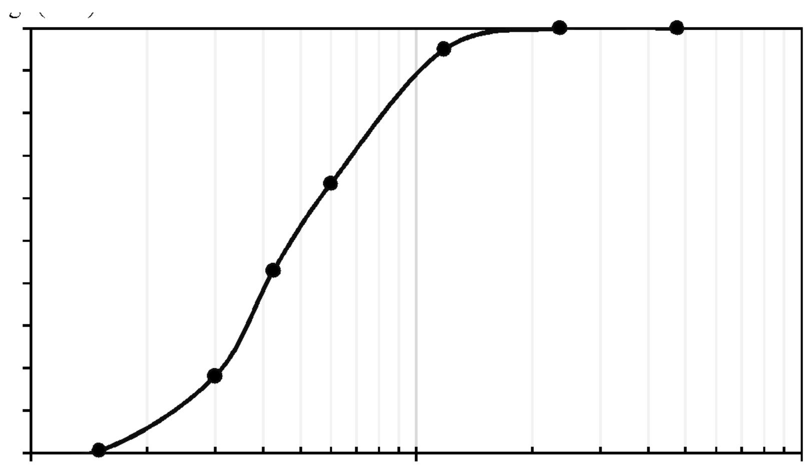


Figure 1: Grain size distribution curve of Sand

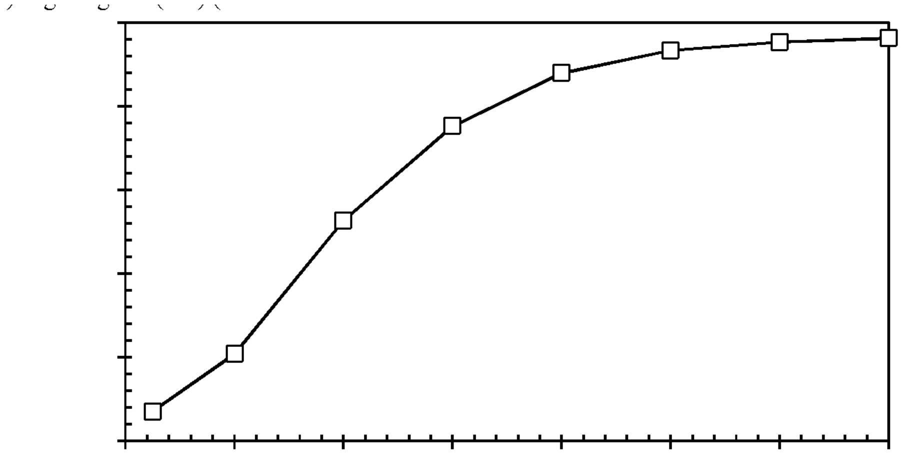


Figure 2: Calibration curve used in sand pluviation method

Table 1: Properties of dry sand

Property	Value
Specific gravity	2.67
Maximum dry density (kN/m^3)	17.27
Minimum dry density (kN/m^3)	15.23
D_{50} (mm)	0.48
Friction angle (ϕ°)	32.5
Maximum void ratio (e_{max})	0.753
Minimum void ratio (e_{min})	0.546

Table 2: Properties of model geosynthetics

Property	Non-woven Geotextile (NGT)
Material	PP
Tensile Strength at 2% Strain (kN/m)	0.025
Tensile Strength at 5% Strain (kN/m)	0.075
C_i	0.997
C_i = Sand-reinforcement interaction coefficient at R.D of 90%	

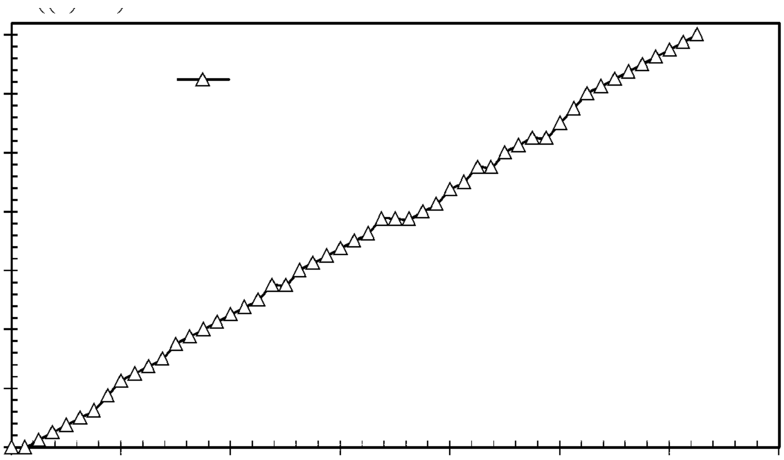


Figure 3: Load-elongation behaviour of model geosynthetic used in the study

3 Experimental Set-up

3.1 Model Parameters and Instrumentation Details

The model footing tests were conducted within a container of length 0.76 m, a height of 0.46 m, and a width of 0.1 m. The schematic view and details of the container are shown in Figure 4. The front face is made of perspex sheet to observe deformations in the soil mass during experiments. The container was sufficiently rigid to maintain plane strain conditions for the tests. The model strip footing had a width of 60 mm, and was centered in the model container with its length running parallel to the container's width. Several uniformly spaced permanent markers were placed on the perspex sheet to aid deformation measurements below the footing using the particle image velocimetry (PIV) technique. Particle image velocimetry (PIV) is a novel geotechnical testing technique that uses digital cameras to monitor soil deformation within the soil mass [9]. PIV technique is a unique subset of the Digital Image Correlation approach. This approach combines numerical computing with digital image processing. A digital camera was thus used in the study to capture the images of the front side of the model container at regular intervals of 10 seconds during the progress of the experiment. The camera can monitor the entire area below the footing for subsequent utilization in the PIV technique, to determine the horizontal and vertical displacements of the soil face. The ratio of container length to footing width was kept at 13 in this experiment, which was enough to eliminate boundary effects. This is based on a similar experimental observation [12], where a ratio of the length of container to width of model footing exceeding 12 was reported to have no effect on load settlement behaviour of the model footing.

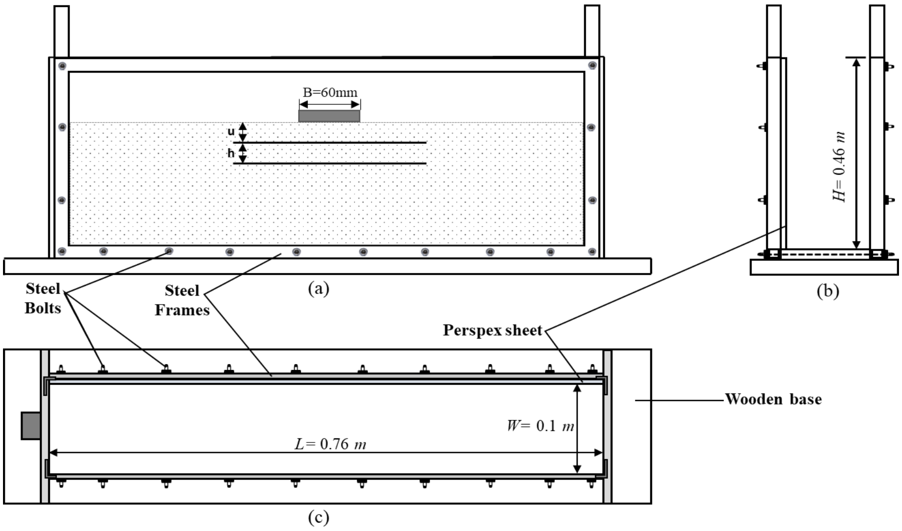


Figure 4: Schematic views of model container (a) Front view (b) Side view (c) Plan

3.2 Sand Bed Preparation and Testing Program

At the outset, the sand was filled in the tank at the required density to achieve general shear failure in course of experimentation. The relative density (Dr) was maintained at 90% (ρ_{dry}= 1.704 Mg/m^3) throughout the testing. The sand was pluviated in layers and was lightly compacted in the tank with a wooden block to achieve a consistent layer thickness of roughly 50mm. Horizontal lines at 50 mm intervals were drawn on the outer face of the container to establish a thickness of 50 mm. This process was repeated for unreinforced tests until the height of sand deposit attained 0.40 m. For tests involving reinforcement, the sand surface was levelled to place a geotextile layer on the foundation, once the sand reached the height of a reinforcement layer. The sand was then again pluviated and densified to the desired relative density. The procedure was continued until the overall thickness of sand deposit reached the desired level.

Several sand depositions were done in the tank before the actual experiments. In these trials, the relative density error was less than 3%. The container was put underneath the loading system and adjusted to ensure that the strip footing was in the middle of the foundation model after the reinforced sand foundation model was prepared. Following that, a load cell was placed to measure the load, and a linear variable displacement transducer (LVDT) was used to measure the footing settlement induced by loading. The front side of the model container was made of a perspex sheet, on which several uniformly spaced permanent markers were placed to aid in deformation measurements below the footing using the particle image velocimetry (PIV) technique. To remove the effect of surrounding lights on the photographs, a strip of lights was positioned in front of the container in a rectangular pattern. The complete set-up was covered with a large piece of cloth at the time of testing to guarantee the same intensity of lighting during the experiment. The displacement vectors and deformation patterns of sand were subsequently computed using GeoPIV software.

The following studies on model strip footing were carried out using the experimental set-up and loading method stated before to explore the behaviour of the strip footing on the geosynthetic-reinforced sand under displacement-controlled conditions. Table 3 shows the outline of laboratory model tests conducted during the experiment. As can be observed from Table 3, tests were conducted on sand without reinforcement, and on sand with multi-layer geotextile reinforcement embedded at different depths.

Table 3: Description of Laboratory Model Test

Reinforcing Material	Number of Layers	*l/B*	*u/B*	*h/B*
Constant Parameters: Relative Density= 90%, B= 60mm, γ_d= 17.04 kN/m^3				
Unreinforced	-	-	-	-
Reinforced with NGT	1	12	0.5	0.25
Reinforced with NGT	2	12	0.5	0.25
Reinforced with NGT	3	12	0.5	0.25

4 Results and Discussion

The main objective of the current research is to investigate the advantages of utilizing geosynthetic reinforcement to reduce the settlement of foundations by employing digital image correlation technique. For this purpose, extensive laboratory model tests were conducted on unreinforced and geosynthetic reinforced sand, as stated previously. The parameters investigated in the model tests include the number of reinforcement layers (*N*) and the vertical spacing between reinforcement layers (*h*). Figure 5 represents the load-settlement curves measured for model footing tests with different layers of reinforcement at different h/B values and for the same *l*/*B* values, where *l* is length of reinforcement and *h* is the spacing between reinforcements.

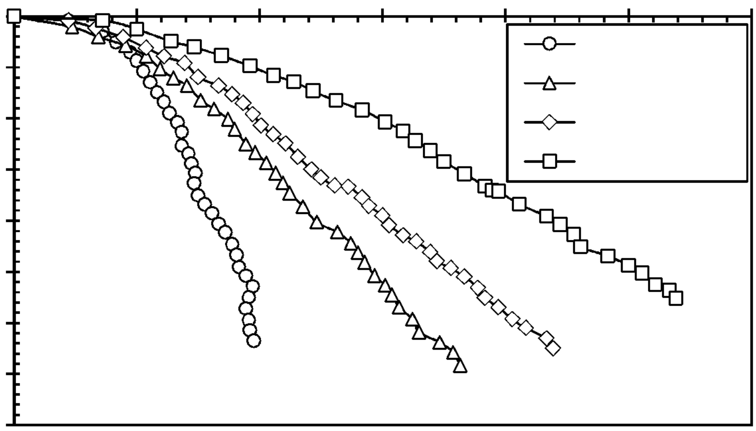


Figure 5: Load-Settlement Curve obtained from model test

The benefit of applying reinforcement is assessed in terms of bearing capacity ratio (BCRs) at a particular settlement based on the observed load-settlement behaviour of the model footing. The bearing capacity ratio (BCRs) is the ratio of the bearing capacity of the reinforced soil foundation to that of the corresponding unreinforced at a specified settlement. Table 4 presents the BCRs obtained at settlement ratios (*s/B*) of 10%, 20%, and 30%, wherein the settlement ratio (s/B) is defined as the ratio of footing settlement (s) to footing width (B).

Table 4: Summary of laboratory model test

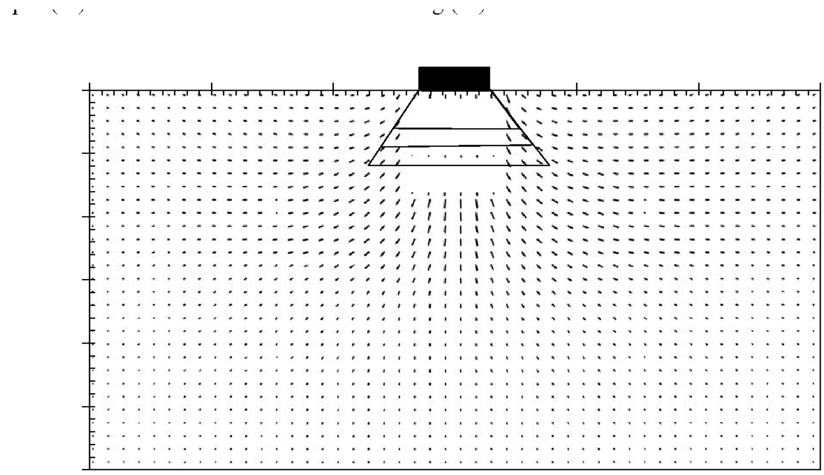
Reinforcement Configuration	u (mm)	h (mm)	s/B = 10%		s/B=20%		s/B= 30%	
			q (kPa)	BCR	q (kPa)	BCR	q (kPa)	BCR
Unreinforced	-	-	52.78	-	66.67	-	73.89	-
N=1	30	15	59.44	1.13	87.22	1.31	106.67	1.44
N=2	30	15	69.44	1.32	100.56	1.51	121.11	1.64
N=3	30	15	96.11	1.82	151.11	2.27	183.33	2.48

In the model footing test, when the top reinforcement layer was placed at 0.5 times the width of the footing, and the reinforcement length was six times the width of the footing, it was observed that upon load application, the reinforcement pulled out the sand present above it. Since tests were performed at 1g, the confinement capacity was less, which could have contributed to the pull-out of the geosynthetic prior to failure. However in the field, failure occurs reportedly by the elongation of geosynthetics. Hence, for simulating field conditions, the length of reinforcement was subsequently increased, and for the remaining experiments, the top reinforcement spacing was considered as 0.5 times the width of the footing, and the length of reinforcement as 12 times the width of the footing. By examining the load-settlement curves presented in Figure 5, it can be observed that the bearing pressure increases as the settlement increases for both reinforced and unreinforced sand deposit. The observed settlement pattern is comparable to that of general shear failure, as anticipated.

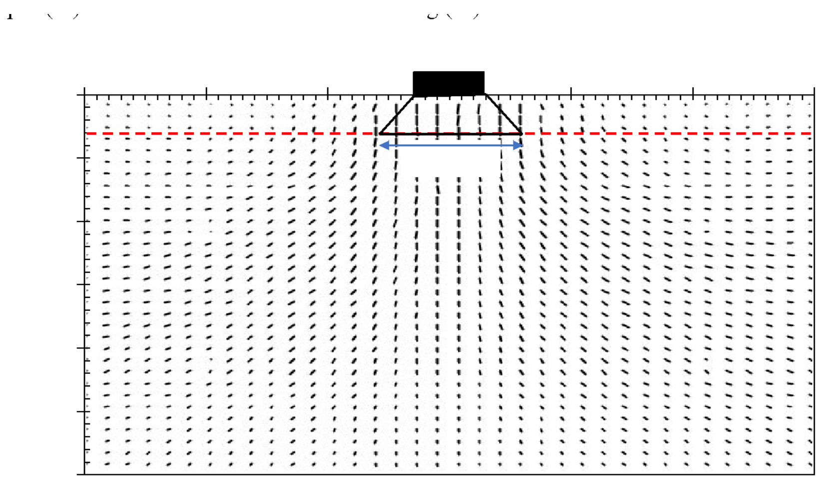
4.1 Effect of Number of Reinforcement Layers on the Load-Spread Angle

The load spread angle (β) is the angle at which the load is distributed. It is reported that the reinforced bed has a higher load-spread angle value than the unreinforced bed, and usually ranges from 25 to 30 degrees [13]. Further, the L/B ratio of rectangular footings and the number of reinforcement layers can affect the load-spread angle [14]. The displacement vectors obtained from PIV analysis in the present study indicated that increase in number of reinforcements cause a decrease of increment rate.

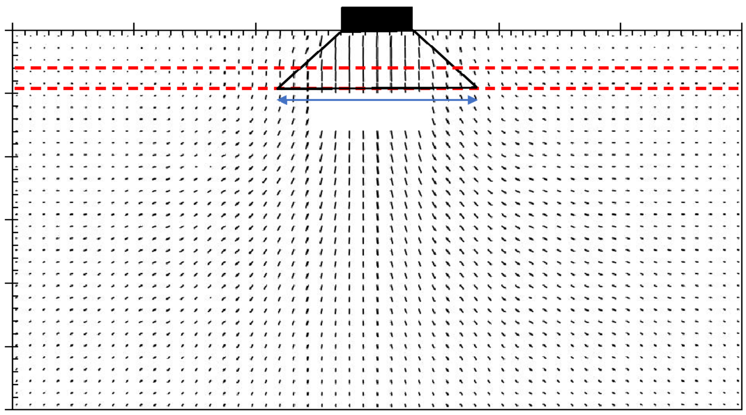
Using the PIV approach, the load distribution mechanism of the geosynthetic-reinforced section and unreinforced section is shown in Fig. 6. The vector movements was used to calculate the width of the load distribution area at the base of the geosynthetic layer. The following process was used to calculate the load spread angle from the picture analysis: (i) The image was digitized and output data generated, (ii) vertical displacement vectors were measured at the horizontal line indicating the position of each reinforcement layer. (iii) The displacement of the soil particles from their orientation at the reinforcement line was used to determine the width of the load distributed area, as beyond this line, the displacement vectors became almost horizontal, (iv) From the horizontal distance contour (*X* mm), the base width of the load dispersion region was calculated as ($B + \Delta B$), and the height of the soil above this layer was calculated as ($h + u$), which is equal to the height of the reinforcing layer. The dispersion angles were computed for each test configuration using the above procedure, as summarized in Table 5.



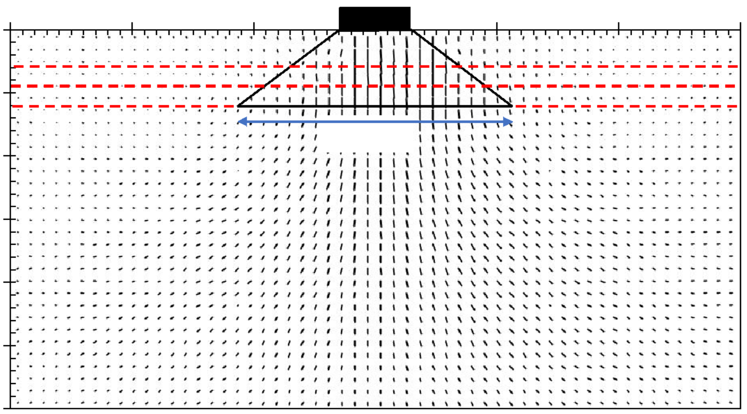
(a) Unreinforced footing at s/B=10%



(b) N=1 layers of reinforcement at s/B=10%



(c) N=2 layers of reinforcement at s/B=10%



(d) N=3 layers of reinforcement at s/B=10%

Figure 6: Load distribution mechanism of unreinforced and geosynthetic reinforced sand obtained using PIV technique

Table 5: Summary of spread angle observed in model test

Reinforcement Configuration	u (mm)	h (mm)	s/B = 10%			
			B+ΔB (mm)	h + u (mm)	ΔB/2 (mm)	α (°)
Unreinforced			80	30	10.0	18.4
N=1	30	15	90.2	30	15.1	26.7
N=2	30	15	126.4	45	33.2	36.4
N=3	30	15	174	60	57.0	43.5

5 Conclusions

The study involves the development of a small-scale physical model for analyzing the settlement profiles under shallow strip footing resting on geosynthetic reinforced sands. A series of experiments were performed by pluviating sand at a relative density of 90%, and by varying the number and spacing between the subsequent reinforcing layers. The tests were performed under displacement-controlled conditions, and instrumented using a load cell and linearly variable displacement transducer (LVDT). The results were interpreted by plotting the load-displacement curve and the displacement vectors obtained through PIV analysis. Based on the analysis and interpretation of the results, the following major conclusions can be drawn:

1) The load-settlement curves registered higher values for the reinforced foundation in comparison to an unreinforced foundation under displacement-controlled conditions
2) The reinforcement was effective in controlling heaving of the foundation sand
3) It was found that adding a third layer of reinforcement significantly improves the bearing capacity ratio (BCR) of the footing, as compared to adding the first two layers.
4) The load-spread angle was found to increase with the number of reinforcement layers, and the rate of this increase reduced with increasing reinforcement layers.

In conclusion, it may be stated that the present research is thus helpful in situations where it is required to construct heavy structures supported on robust foundation systems on sandy soils, by providing geosynthetic reinforcements at different layers within the sandy soil. Geosynthetics reinforce the soil and are cost-effective, and additionally reduce the foundation settlement and increase the bearing capacity.

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