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ORIGINAL PAPER

Effect of Submergence on Settlement and Bearing Capacity of Surface Strip Footing on Geotextile-Reinforced Sand Bed

Monir Kazi · Sanjay Kumar Shukla · Daryoush Habibi

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Abstract This paper presents the effects of submergence on the settlement and the bearing capacity of a surface strip footing resting on the reinforced sand bed at a relative density of 90 % by conducting the laboratory model tests. The reinforcement layers used were woven geotextile layers, without and with wraparound ends. The number of reinforcement layers was varied from 1 to 4. The test tank had an arrangement for the water table rise, from the bottom of the sand bed constructed in the tank. The model strip footing was placed at the surface of the sand bed, and measurement of the settlement occurring with the rise of the water table, was taken to observe the effect of water table rise. When the water table reached the top surface of the sand bed, that is, the sand bed was fully submerged under water; the measurement of settlement of the footing was continued, by applying the load incrementally through the hydraulic jack. The results show that the rise of the water table causes a significant settlement of the footing for both unreinforced and reinforced cases. However, the beneficial effect of reinforcement layers was observed in terms of increased load-bearing capacity. An increase in the number of reinforcement layers, from 1 to 4 as well as providing the wraparound ends to the reinforcement, brought a significant increase in load-bearing capacity. When compared to the dry situation, there is a significant decrease in the load-bearing capacity as well as in the modulus of subgrade reaction of the unreinforced and reinforced sand beds with the rise of water table and full submergence.

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Keywords Bearing capacity · Sand bed · Settlement · Strip footing · Submergence · Water table rise

List of Symbols

Basic SI units are given in parentheses

B	Width of footing (m)
b	Width of reinforcement without wraparound ends (m)
b'	Width of reinforcement with wraparound ends (m)
c	Cohesion (kPa)
C_c	Coefficient of curvature (dimensionless)
C_u	Coefficient of uniformity (dimensionless)
D_{10}	Effective particle size (m)
d	Depth of reinforcing zone from the base of the footing (m)
d'	Distance above the horizontal straight portion of reinforcement layer (m)
D_f	Embedded depth of foundation
D_r	Relative density (%)
E	Young's modulus (N/m^2)
EA	Axial stiffness (N/m)
EI	Flexural rigidity (Nm^2/m)
h	Sand column depth within the jars (m)
Δh	Settlement of sand column within the jars (m)
H	Thickness of sand bed in the model tank (m)
ΔH	Settlement of sand bed due to water table rise in the model tank (m)

H_{WT} Height of water table in an individual stage (m)
k_s Modulus of subgrade reaction (N/m^3)
k_{sU_0} Modulus of subgrade reaction for unreinforced soil with surface footing (N/m^3)
I_b Ultimate load-bearing capacity improvement factor
I_s Modulus of subgrade reaction improvement factor
l Lap width of reinforcement (m)
q Load-bearing pressure (N/m^2)
q_u Ultimate load-bearing capacity (N/m^2)
q_{uR} Ultimate load-bearing capacity of the reinforced soil (N/m^2)
q_{uU_0} Ultimate load-bearing capacity for unreinforced soil with surface footing (N/m^2)
R_{inter} Strength reduction factor (dimensionless)
s Settlement of the footing (m)
S Degree of saturation (%)
ε Vertical spacing of reinforcement layers
u Depth of the first geotextile reinforcement layer from the base of the footing (m)
ϕ Angle of internal friction (degrees)
γ_d Dry unit weight (kN/m^3)
$\gamma_{d\max}$ Maximum dry unit weight (kN/m^3)
$\gamma_{d\min}$ Minimum dry unit weight (kN/m^3)
μ Poisson's ratio (dimensionless)
ψ Angle of dilatancy (degrees)

Introduction

Sandy soils, generally used as structural fills, are typically screened earthen materials obtained from the borrow pits and quarries for various civil engineering applications [1, 2] such as foundation soils, embankment materials, and backfills behind retaining walls. They are selected, placed and compacted to an appropriate specification in order to achieve the required engineering performance [3]. In Perth and its surrounding area, a large amount of fill is routinely used by the construction industries, especially for constructing pavement bases and foundations for residential buildings. The authors have experienced that though the sand base layer is able to provide a perfectly level structural base for laying the footings, undulations due to differential settlements appear over time, especially after submergence under water. As a consequence, structural/architectural failure subsequently takes place. Terzaghi [4] postulated that the submergence of the sand reduces the soil stiffness by half, which in turn doubles the settlement [5, 6]. This proposition was supported by a number of other researchers [7–10]. However by conducting laboratory model tests, Murtaza et al. [11] have observed that the settlement in submerged conditions can cause 8–12 times more settlement, depending on the relative densities of the sand. Morgan et al. [12] have also found that an increase in settlement in submerged conditions can be 3.2–5.3 times the settlement for the dry sand for very dense condition to very loose condition, respectively. Shahriar et al. [13] have presented a critical review of the effect of submergence on soil settlement of shallow foundations. The settlement of a shallow foundation is generally not allowed to exceed some specified value, say 25–50 mm.

A large number of model tests and numerical studies have been reported in the literature, aimed at developing a cost-effective and convenient approach, for using the geosynthetic reinforcement to increase the load-bearing capacity of shallow foundations. Most studies have been conducted by employing one or more geosynthetic reinforcement layers, laid horizontally within the dry sand bed supporting a footing [14]. Recently, the authors have reported [15] that the geotextile reinforcement with wraparound ends requires a lower width of the land for the construction of geosynthetic-reinforced foundations, and it also causes additional increase in the load-bearing capacity and stiffness, compared with geosynthetic layer(s) laid horizontally without wraparound ends within the dry sand bed. The literature is almost silent regarding the quantitative effect of submergence of geotextile-reinforced sand beds on the settlement behaviour and load-bearing capacity of the footing. As a consequence, an attempt is made to present the methodology and findings arising from the present investigation into the effect of submergence on the load-settlement behaviour of a strip footing resting on a very dense fill, reinforced with geosynthetic reinforcement, both with and without wraparound ends. The selection of very dense fill was made, based on the submergence study of sand at different relative densities in the laboratory; and this is also presented here.

Materials

In Perth and its surrounding area, there are a number of sites from where the sandy soils are usually quarried. In this present work, the most commonly used sandy soil, called the brickies sand, was collected from a site about 40 km North of

Fig. 1 The quarry site for the soil

Perth's CBD (Fig. 1). All the physical properties of the sand were determined as per the relevant Australian standards listed in AS: 1289 [16], and are given in Table 1. Figure 2 shows the particle-size distribution curve for this sand, and Fig. 3 shows the compaction test results. The sand is classified as a poorly graded sand (SP) as per the Unified Soil Classification System (USCS). The reinforcement used in the tests was a woven geotextile manufactured from high strength polyester (PET) yarns, having the properties as: thickness = 35 mil, mass per unit area = 445 g/m^2, tensile strength (machine direction) = 200 kN/m, tensile strength (cross-machine direction) = 50 kN/m, and the tensile strain corresponding to the tensile strength 200 kN/m = 10 %.

Effect of Submergence

When a sand bed is placed and compacted properly, it provides a firm foundation for supporting buildings or other structures. Since there are always limitations on the acceptable amount of settlement, the volumetric change within the fill upon its submergence is usually of main concern [17, 18]. All the previous researchers indicate that the submergence creates settlement in the sand bed, but their settlement predictions/observations differ significantly. It is widely recognized that for a dry sand bed, the relative density of the soil always plays a significant role in load-bearing capacity. To investigate the submergence effect on the settlement of a sand fill having a range of different relative densities, a simple laboratory submergence test was carried out by using five calibrated cylindrical jars as shown in Fig. 4. All the jars were filled to a height h = 158 mm, to maintain a constant volume in each jar up to 300 ml, with sand having the following relative densities: D_r = 0, 25, 50, 75 and 100 %. Water was poured into each jar in order to achieve complete submergence;

Table 1 Properties of soil

Property	Value
Specific gravity	2.66
Maximum dry unit weight, $\gamma_{d\max}$ (kN/m^3)	15.98
Minimum dry unit weight, $\gamma_{d\min}$ (kN/m^3)	13.92
Maximum void ratio	0.84
Minimum void ratio	0.57
Effective particle size, D_{10} (mm)	0.18
D_{60} (mm)	0.38
D_{30} (mm)	0.26
Coefficient of uniformity, C_u	2.11
Coefficient of curvature, C_c	0.99
Soil group as per USCS	SP
Relative density, D_r (%)	90
Peak friction angle, ϕ_{peak} (°)	38
Ultimate friction angle, ϕ_{ult} (°)	32
Cohesion, c (kPa)	7.25

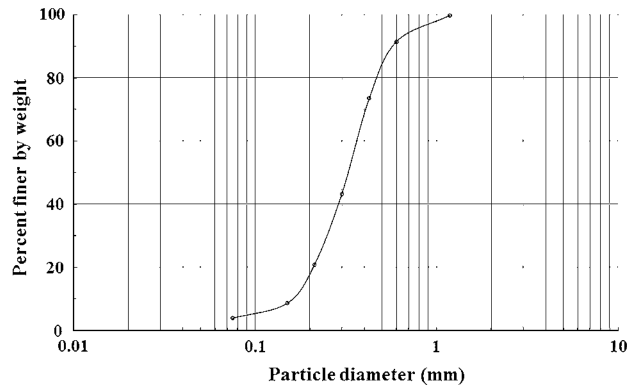

Fig. 2 Particle-size distribution of the soil

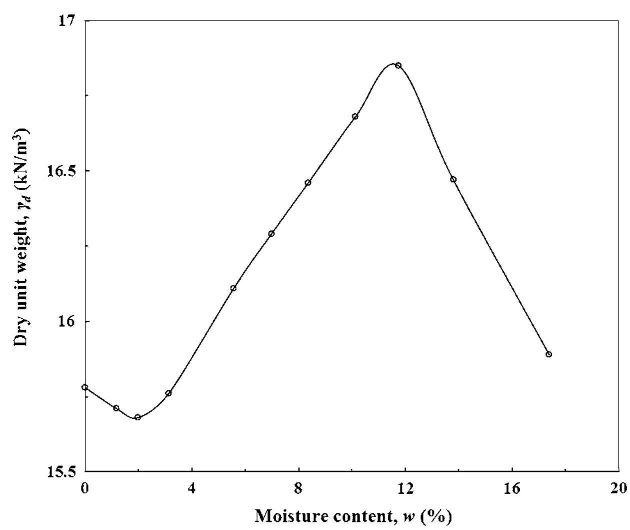

Fig. 3 Variation of the dry unit weight of soil with the moisture content

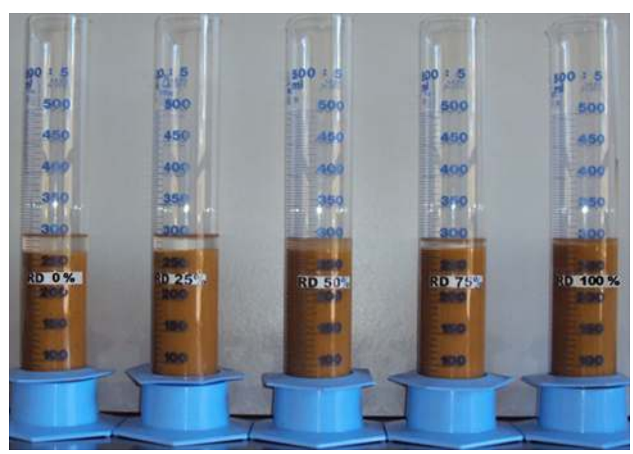

Fig. 4 Sand columns at different relative densities under submerged condition

but taking care not to exceed the total volume of sand and water beyond 300 ml. All the jars were held for 24 h in the submerged condition so as to achieve thorough saturation; after which the values of the final settlements (Δh) were recorded. It was noticed that with submergence, the sand was always caused to settle, and the settlement was greatest in the jar having sand with $D_r = 0$ %, and was least in the jar having sand with $D_r = 100$ %, as seen in Fig. 4.

Figure 5 represents the variation of the settlement ratio ($\Delta h/h$) with the relative density of the sand column within the jars, whilst in the submergence condition. It is noticed that the settlement ratio decreases at a slightly decreasing rate as the relative density increases. For example, the settlement ratio decreases by 1.9 % with an increase in relative density from 75 to 100 %, whereas the decrease in settlement ratio is 3.1 % for the increase in relative density from 0 to 25 %. Thus this simple experiment shows that the sand bed, when it becomes submerged, undergoes a large settlement for sand of lower relative density. In practice, the sand bed can easily be compacted to a very dense condition. Moreover, for a very dense condition, the settlement caused by submergence is limited; so a value of $D_r = 90$ % was considered in the model load tests.

Model Footing Load Test

As explained in the preceding section, it is observed that even when the sand bed has been fully compacted to its maximum dry unit weight; there is always some settlement by submergence. In view of this fact, a series of laboratory model tests were conducted for investigating the load

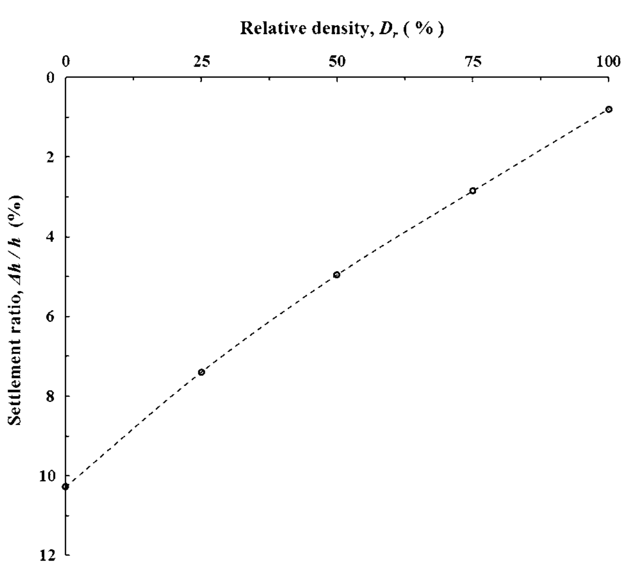

Fig. 5 Variation of the settlement of the sand fill caused by submergence with relative density

settlement behaviour and bearing capacity of a surface strip footing. The strip footing is resting on a very dense sand bed under submerged condition, for unreinforced and reinforced cases, where the reinforcement is either without or with wraparound ends. It may be noted that for the surface footing as considered in this study, the ratio of footing embedment depth D_f, to its width B, is zero throughout the present study.

Preparation of Sand Bed and Test Arrangement

Figure 6a–d show the schematic view of the laboratory test arrangements. The laboratory model tests were carried out in a tank with internal dimensions of 1,200 mm length, 400 mm width, and 800 mm height. The tank was fabricated from 25 mm thick Perspex sheet braced with structural steel members. The load reaction frame was attached to the tank. The model footing used for the tests was a strip footing made of a 40-mm thick rigid steel plate. The length and width of the footing were 390 and 80 mm, respectively. The base of the model footing was roughened by cementing a thin layer of sand to it with epoxy glue. The model tests were conducted based on the relative density of sand bed as $D_r = 90$ %, resulting in a total dry unit weight of 15.75 kN/m^3. The test tank was filled with sand in four layers; each compacted layer was approximately 160 mm thick; maintaining a total thickness of the sand bed of 640 mm. Each layer of sand was compacted with a 25 mm diameter vibratory poker to achieve the desired relative density. Proper care was given to achieve the same dry unit weight in all the four lifts, in order to have a homogenous sand bed. In each of the test trials, the geotextile layer had its machine direction parallel to the width of the footing. The sand above the straight portion of the geotextile, and around its wraparound ends, was compacted by ramming with a hand rammer, because the vibratory poker could have damaged the geotextile reinforcement. It is important to mention that when using the hand rammer; several preliminary tests were carried out to determine the number of blows required for achieving the desired relative density of sand above straight portion of geotextile, as well as around its wraparound. The footing was always placed at the centre of the tank, below the load-reaction frame, to avoid eccentric loading. For measuring the footing settlements, two dial gauges spaced equally from the centre of the footing, were used. The readings obtained from the dial gauges were averaged to determine the settlement. Water has been filled into the tank through four transparent rubber tubes attached to the four corners as shown in Fig. 6a, b. The water table was raised in eight stages, each of depth 80 mm (which is equivalent to the footing width B), starting from the bottom of the tank to the footing base level. The rising height of the water table was monitored

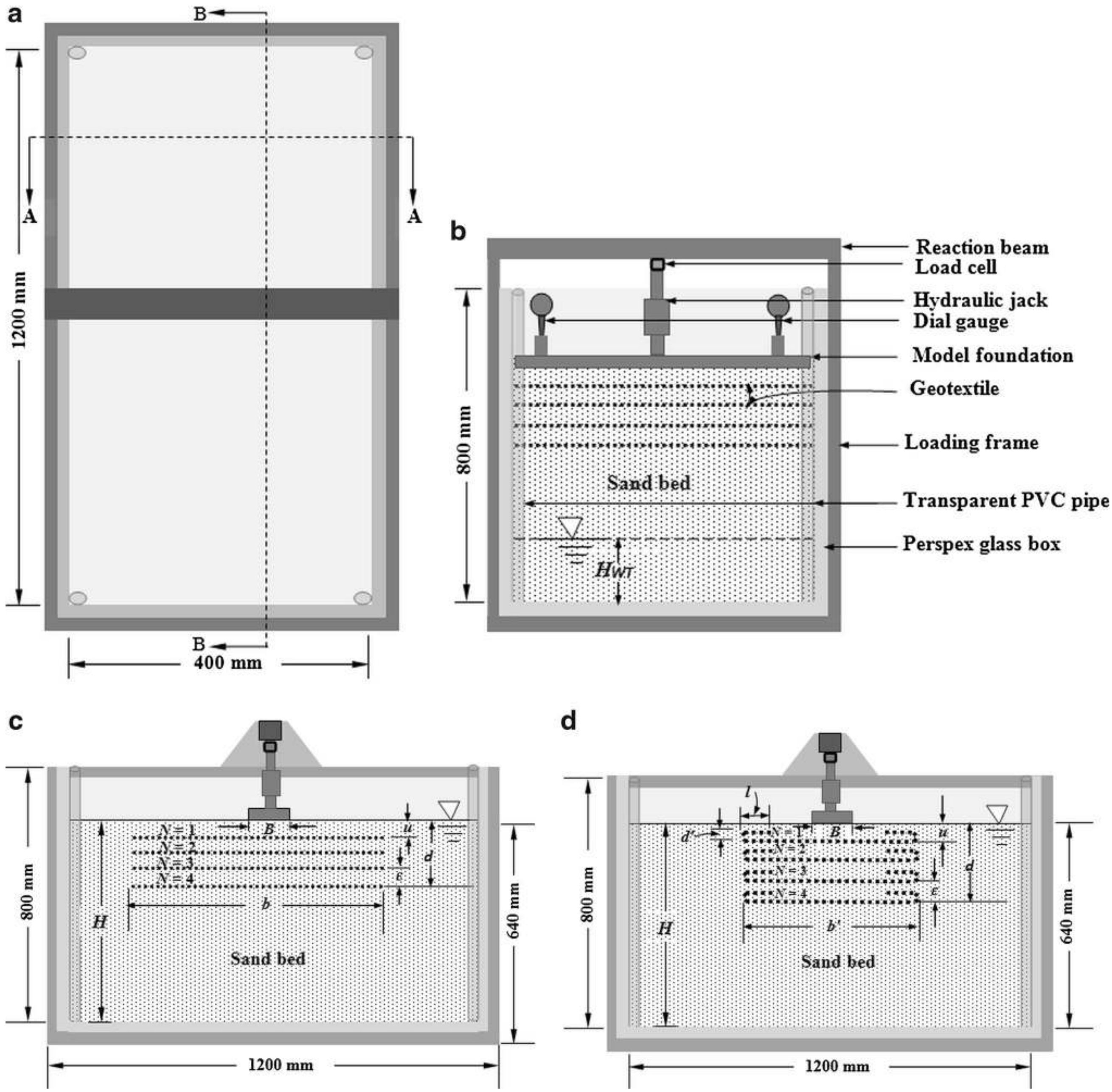

Fig. 6 Laboratory test arrangement; **a** plan **b** cross-section *A–A* **c** cross-section *B–B* (reinforcement layer without wraparound ends) **d** cross-section *B–B* (reinforcement layer with wraparound ends) (Not to scale)

through the transparent rubber tubes; and the time between two successive increments to the height of the water table, was always kept constant. The settlement caused by the incremental rise of the water table, was determined for each separate stage. Figure 6c shows the typical layout of a reinforced sand bed adopted for the model as part of the test, where the reinforcement layers were placed without wraparound ends. The number of reinforcement layer is indicated by *N*, each layer having a width of *b*. The top layer of the reinforcement is placed at a depth *u* from the bottom of footing; and ε is the vertical spacing between two consecutive geosynthetic layers. The total depth of reinforcement layers from the bottom of the footing is *d*. The magnitude of the bearing capacity for the footing depends on *b*/*B*, ε/*B*, *u*/*B*, and *d*/*B*, for the reinforcement arrangement without wraparound ends [14, 19]. Figure 6d shows the typical layout of a reinforced sand bed adopted for the model tests where the reinforcement layers were placed with wraparound ends. The total width of the reinforcement layer *b* is

$$b = b' + 2(l + d') \quad (1)$$

where l is the lap width at a distance d' above the horizontal straight portion of the reinforcement layer of width b'. The magnitude of the load-bearing capacity of the strip footing will depend on: b'/B; ε/B; u/B; l/B; D_f/B; d'/B; and d/B, for the wraparound reinforcement arrangement situation. For the maximum reinforcement benefit of a surface strip or rectangular footing, resting on a reinforced sand bed, reinforced with a multiple horizontal straight reinforcement layers, the following typical parameters have been reported in the earlier studies: $b/B = 6$ [20]; $N = 4$ [21]; $d/B = 1.5$ [21]; $u/B = 0.25$–0.5 [21, 22]; $\varepsilon/B = 0.2$–0.4 [21].

Recently the laboratory model tests with surface footings were carried out to observe the effects of wraparound ends of the geotextile reinforcement on the load-settlement behaviour of the reinforced dry sand bed, with several layers of geotextile reinforcement [15, 23]. These studies show that the introduction of wraparound reinforcement provides significant benefits in terms of strength and stiffness, where $u/B = 0.3$, $N = 4$, and $d/B = 1.2$. In view of the earlier findings, the following parameters were adopted in the subsequent tests conducted in the present study:

For reinforcement without wraparound ends,

$$b/B = 6; \quad \epsilon/B = 0.3; \quad u/B = 0.3; \quad N = 1, 2, 3 \text{ and } 4; \quad d/B = 1.2$$

For reinforcement with wraparound ends,

$$b'/B = 4; \quad \epsilon/B = 0.3; \quad u/B = 0.3; \quad l/B = 0.6; \quad d'/B = 0.2; \quad N = 1, 2, 3 \text{ and } 4; \quad d/B = 1.2$$

It may be noted that $N > 4$ has not been considered here. This is mainly because a higher number of reinforcement layers will not bring any significant improvement in load-bearing capacity. This decision was based on the tests conducted on the laboratory apparatus, comprising of a surface strip footing resting on a dry sand bed, reinforced with several layers of the geotextile reinforcement, both without and with wraparound ends [23].

Test Procedure

A series of load settlement tests were conducted on a very dense sand bed under conditions of full submergence. After preparing the sand bed and making all arrangements as shown in Fig. 6, the test started with the first stage of raising the water table; with the initial dial gauge reading zero, and without any application of load on the footing. As described earlier, the tank was filled with water through the rubber tubes until the water table reached a height of 80 mm. When the dial gauge readings were stabilized, they were noted down, and the settlement during that stage of raising the water table was determined. The water table was raised further (in seven more stages), to allow the water table to reach the base level of the footing. The settlements caused during all stages of water table rise, were measured. Figure 7 shows the model footing load test arrangement in the laboratory under full submergence of the sand bed. In order to observe the load-settlement response of the footing under the applied load; a normal compressive load was applied to the footing, by means of a 100-kN hydraulic jack against the reaction beam, in increments of 0.312 kN, resulting in a pressure of 10 kN/m^2. The load increments were monitored using a load cell of 100-kN capacity. Each load increment was kept constant until the footing settlement was stabilized. The load on the footing was continued to increase until the soil around the footing failed by noticeable heave around the footing, or a tilt of the footing was noticed, indicating almost a general shear failure. To ensure standardised conditions throughout the investigation, the test tank was emptied and refilled with sand, as well as submerged under water, for tests with other varying conditions. The variation of settlement caused by the rising water table and the load-bearing pressure (q) versus settlement (s) data were plotted, along with a discussion of the results in the next section.

Results and Discussion

Figure 8a shows the variation of the settlement ratio (s/H) with the height of water table (H_{WT}) arising from the tests conducted on the experimental apparatus. It is observed that the settlement of the sand bed increases with increasing height of the water table. It is also noticed that the rate of the settlement decreases with the rise of the water table, and becomes constant when the water table reaches the footing base level. It is noted that when the

Fig. 7 Model footing load test arrangement under submerged condition

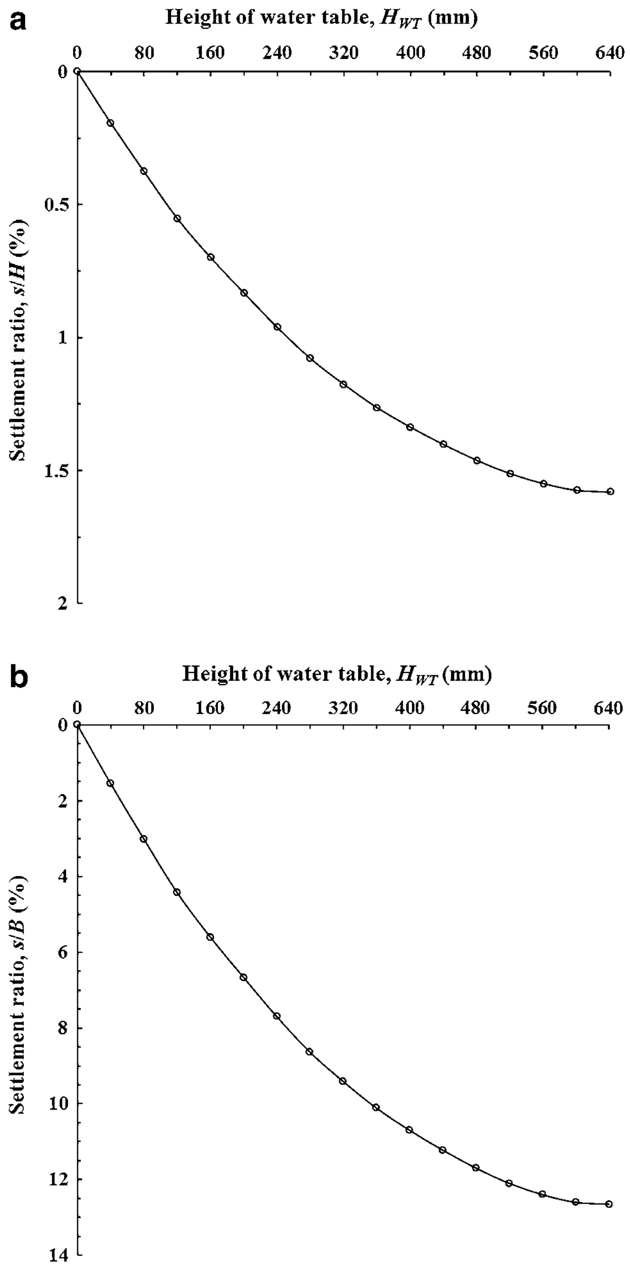

Fig. 8 **a** Variation of settlement ratio *s*/*H* with the height of water table H_{WT}, and **b** variation of settlement ratio *s*/*B* with the height of water table H_{WT}

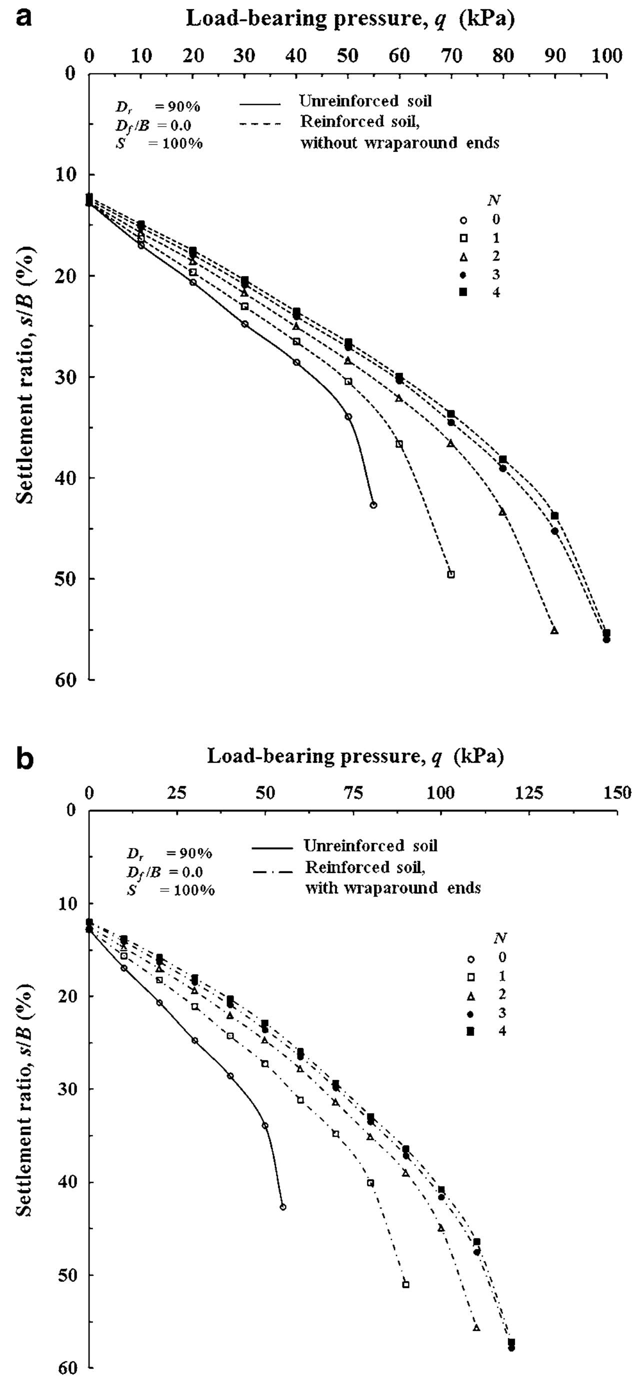

Fig. 9 Load-bearing pressure (*q*) versus settlement ratio (*s*/*B*)—effect of number of reinforcement layers (*N*) **a** reinforcement without wraparound ends; and **b** reinforcement with wraparound ends

water table reaches the footing base level, the settlement ratio (*s*/*H*) is 1.58 %, which is approximately the same as the settlement ratio ($\Delta h/h$) as observed in the previously described jar experiment for $D_r = 90$ %. Similar to Fig. 8a, the variation of the settlement ratio (*s*/*B*) with the height of water table (H_{WT}) is shown in Fig. 8b. It is probable that the settlement of the footing after submergence, results from the breakdown of bonds between the soil particles. A second probable cause of the settlement can be explained in part by the lubrication mechanism of the soil particles in the presence of water. These factors result mainly in a loss of soil strength and stiffness/modulus when the soil bed is submerged under water [4–6, 12, 13].

Figure 9a–b show the variation of load-bearing pressure (*q*) with settlement ratio (*s*/*B*), for unreinforced and reinforced soils (without and with wraparound ends) where: 1) the number of reinforcement layers $N = 0$, 1, 2, 3, and 4; and 2) the surface footing is on the sand bed under fully submerged conditions (degree of saturation, $S = 100$ %). It is noted that the initial settlement of about 12.65 % at zero applied pressure on the footing, is caused by the rise of the water table up to the base of the footing. It should be noted that $N = 0$ represents an unreinforced sand bed. It is observed that as the load-bearing pressure increases, the settlement of the footing continues to increase until the sand bed fails, for both unreinforced and reinforced cases. For a given applied pressure, the settlement is lower as the number of reinforcement layer increases; and is lower again with the addition of wraparound ends of the geotextile reinforcement.

From the load-settlement curves presented in Fig. 9a–b; the ultimate load-bearing capacities can be determined by noting the load-bearing pressure, corresponding to the point at which the pressure-settlement curve becomes steep and straight [4, 6]. The variation of the ultimate load-bearing capacity q_u with the number of reinforcement layers N (without or with wraparound ends) is shown in Fig. 10. The ultimate load-bearing capacity for unreinforced and reinforced sand beds are typically denoted as q_{uU} and q_{uR}, respectively. For a generalised graphical representation, q_u refers here to the ultimate load-bearing capacity of the sand bed, for all cases. It is observed that as N increases, q_u also increases. The effect of increase in the number of reinforcement layers on the ultimate load-bearing capacity, is observed to be most significant up to $N = 3$ for the surface footing. In the earlier work without submergence, it has been found that the effect of the number of reinforcement layers on the ultimate load-bearing capacity is observed to be more significant up to $N = 4$ for the surface footing [23]. Table 2 provides the ultimate load-bearing capacity values for the surface footing resting on a dry sand bed, along with the ultimate load-bearing capacity values for the submerged condition, in the case where there is only a single layer of reinforcement. It is found that the submerged sand bed in a very dense condition behaves like a dry sand bed in a medium dense condition.

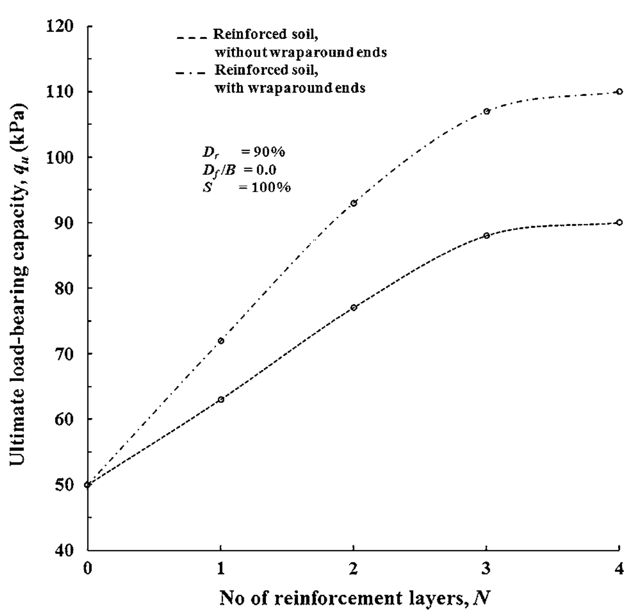

Fig. 10 Variation of ultimate load-bearing capacity (q_u) versus number of reinforcement layers (N)

From the load-settlement curves presented in Fig. 9a–b, the modulus of subgrade reaction (k_s) is calculated as the load-bearing pressure per unit settlement applied to the footing at 1.25 mm. An initial settlement of about 12.65 % at zero applied pressure, arising from raising the water table up to the base of the footing, is considered to be the base point for calculating the modulus of subgrade reaction (k_s). Figure 11 shows the variation of k_s with the number of reinforcement layers (without or with wraparound ends) for reinforcement layers $N = 0$, 1, 2, 3 and 4 for the footing on the sand bed under conditions of full submergence. It is observed that the k_s increases with an increasing number of reinforcement layers, both for geotextile reinforcement without or with wraparound ends. It is also noticed that the cases where there are wraparound ends on the geotextile reinforcement, result in an increase in the modulus of subgrade reaction when compared to the cases of geotextile reinforcement without wraparound ends. The effect of increasing number of reinforcement layers on the modulus of subgrade reaction is noticed to be most significant up to $N = 3$, whereas significance up to $N = 4$ has been reported for dry sand beds [23]. Table 3 provides the modulus of subgrade reaction values for the surface footing resting on a dry sand bed along with the modulus of subgrade reaction

Table 2 Ultimate load-bearing capacity of the surface footing resting on a single layer reinforced sand bed

Sand bed	Ultimate load-bearing capacity of the surface strip footing resting on the submerged sand bed (kPa)	Ultimate load-bearing capacity of the surface strip footing resting on the dry sand bed (kPa) [14]	
	$D_r = 90$ %	$D_r = 50$ %	$D_r = 90$ %
Unreinforced	50	37.5	224
Reinforced without wraparound ends	63	82.5	390
Reinforced with wraparound ends	72	87.5	447

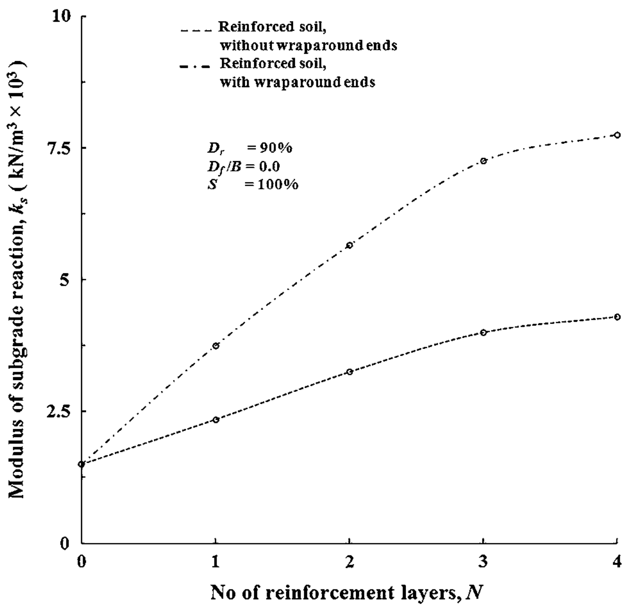

Fig. 11 Variation of modulus of subgrade reaction (k_s) versus number of reinforcement layers (N)

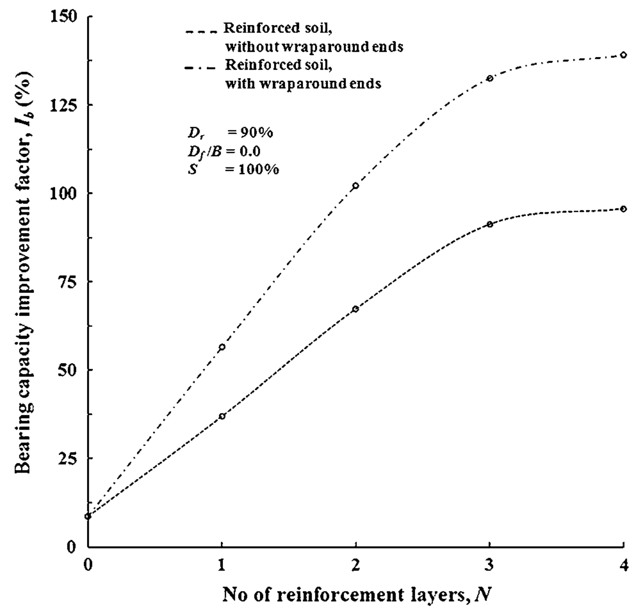

Fig. 12 Ultimate load-bearing capacity improvement factor (I_b) versus number of reinforcement layers (N)

Table 3 Modulus of subgrade reaction of the surface footing resting on a single layer reinforced sand bed

Sand bed	Modulus of subgrade reaction of the surface strip footing resting on the submerged sand bed (kN/m^3 × 10^3)	Modulus of subgrade reaction of the surface strip footing resting on the dry sand bed (kN/m^3 × 10^3) [14]	
	$D_r = 90$ %	$D_r = 50$ %	$D_r = 90$ %
Unreinforced	1.5	3.15	48
Reinforced without wraparound ends	2.35	3.6	84
Reinforced with wraparound ends	3.75	3.6	120

values for the submerged condition for the single layer reinforced case. It may be noticed that under submerged condition, the stiffness of the very dense bed is closer to its stiffness under medium dense dry condition.

For representing the ultimate load-bearing capacity of the reinforced sand bed with respect to an unreinforced soil bed supporting the surface footing, a parameter I_b, called the bearing capacity improvement factor, is defined below [23]:

$$I_b = \left(\frac{q_u - q_{uU_0}}{q_{uU_0}}\right) \times 100 \quad (2)$$

where q_{uU_0} is the ultimate load-bearing capacity of an unreinforced sand bed for the surface footing. It is noted that $I_b = 0$ refers to the case of the surface footing resting on an unreinforced sand bed.

Figure 12 shows the variation of I_b with the number of reinforcement layers (without or with wraparound ends). It is observed that as N increases, I_b also increases in all cases, but the rate of increment decreases after certain number of reinforcement layers. According to the data presented in Fig. 12, the increments in I_b values, that is, the values of ΔI_b, with an increase in the number of consecutive reinforcement layers (e.g. 0–1, 1–2, etc.) are presented in Fig. 13. It is clearly observed that the number of reinforcement layers after $N = 3$, does not bring any significant bearing capacity improvement for reinforced soils with or without wraparound ends cases.

For representing the modulus of subgrade reaction of the reinforced sand bed with respect to an unreinforced soil bed supporting the surface footing, a parameter I_s, called the subgrade modulus improvement factor, is defined below [23]:

$$I_s = \left(\frac{k_s - k_{sU_0}}{k_{sU_0}}\right) \times 100 \quad (3)$$

where k_{sU_0} is the modulus of subgrade reaction of the unreinforced sand bed for the surface footing. It is noted that $I_s = 0$ refers to the case where the surface footing is resting on an unreinforced sand bed.

Figure 14 shows the variation of I_s with the number of reinforcement layers (without or with wraparound ends). It

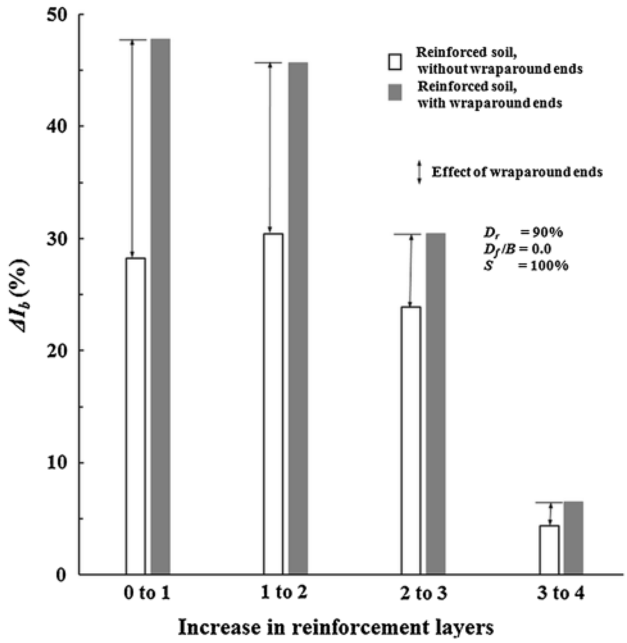

Fig. 13 Ultimate load-bearing capacity improvement with consecutive number of reinforcement layers increase

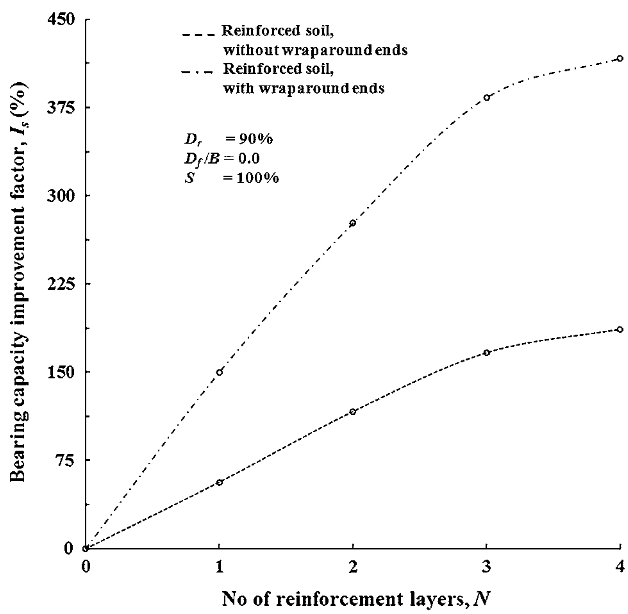

Fig. 14 Modulus of subgrade reaction improvement factor (I_s) versus number of reinforcement layers (N)

is observed that as N increases, I_s also increases in all cases, but the rate of increase slows down after certain number of reinforcement layers. In accordance with the data presented in Fig. 14, the increments in I_s, that is, the values of ΔI_s, with an increase in the number of consecutive reinforcement layers (e.g., 0–1, 1–2, etc.) are presented

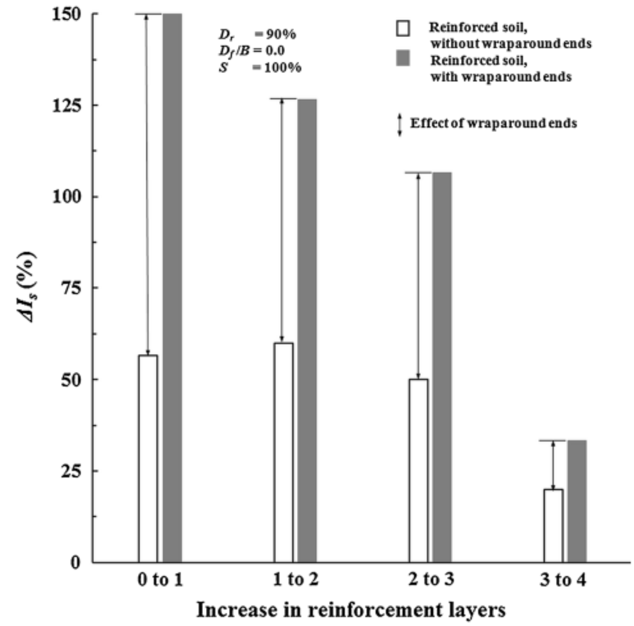

Fig. 15 Modulus of subgrade reaction improvement with consecutive number of reinforcement layers (N)

in Fig. 15. It is clearly observed that the number of reinforcement layers after $N = 3$, does not bring any significant modulus of subgrade reaction improvement, for reinforced soils either without or with wraparound ends.

Concluding Remarks

Based on the study presented in the previous sections, the following general conclusions can be drawn:

1. The simple laboratory experiments have shown that the sand bed settles significantly when it is submerged under water for lower values of relative density. For the very loose sand fill having $D_r = 0\,\%$, the ratio of the settlement to the thickness of sand bed is about 10.3 %, and for the very dense sand fill having $D_r = 100\,\%$, the ratio is about 0.8 %. This trend is also noticed for the sand bed when submerged in the model test tank.
2. An inclusion of the geotextile reinforcement in the sand bed under submerged condition increases its load-bearing capacity and stiffness in terms of modulus of subgrade reaction. The wraparound ends bring additional improvement in the load-bearing capacity and stiffness by the confinement mechanism.
3. Though improvements in load-bearing capacity and stiffness are observed with an increase in number of reinforcement layers, the improvement is not significant for the number of reinforcement layer $N > 3$ for

reinforced soils. This applies to cases either without or with wraparound ends. This finding differs from the observations made in the dry sand fill, where $N = 4$ results in a significant improvement over $N = 3$.

4. The very dense sand fill under the submerged condition behaves like a medium dense dry sand fill, as far as the load-bearing capacity and stiffness of the fill are concerned.
5. This study is based on the laboratory tests conducted on a small-scale model footing; consequently the results obtained may require a suitable modification when being applied to prototype footings. It is expected that the researchers may conduct large-scale model tests in near future.

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