ABSTRACT

Improvement of the bearing capacity of weak soil is one of the potential fields of application of reinforced soil. Though the concept of reinforced soil is simple, the technique has yet not been fully exploited, as there are very few studies available pertaining methods of analysis and design. The reinforcement mechanism is not clearly understood. A program of laboratory scale plane-strain bearing capacity tests under monotonic loading has been carried out which considers the reinforcing mechanism of the Geotextile. The applicability of a method for predicting bearing capacity of sand overlying soft clay with geotextile reinforcement at sand-clay interface is examined by the author using tests performed under various test conditions.

The study included a series of model footing tests on compact sand overlying soft clay sub grade with or without reinforcement at the interface. The following series of tests were conducted under this program.

Series 1: Effect of Depth of Reinforcement (H/B ratio)

The thickness of sand layer (H) to width of footing (B) i.e. H/B ratio was varied from 0.0 to 1.8 at an interval of 0.20, for both unreinforced and reinforced cases and critical H/B ratios were obtained. Tests were conducted for footing shapes namely Strip, Rectangular, Square and circular.

Sixty four experiments performed.
Series 2: Effect of Width of Reinforcement (B’)

Width of reinforcement (B’) to the width of footing (B) i.e. B'/B ratio was varied from 1.0 to 7.0. The critical H/B ratio obtained from series 1 was kept constant for corresponding footing shapes namely Strip, Rectangular, Square and Circular. The critical B'/B ratios were obtained for different footing shapes. Eighteen experiments performed.

Series 3: Effect of Size of Footing

Square footing was selected to examine the size effect on bearing capacity and settlement. Three sizes of square footing namely 150mm x 150mm, 100mm x 100mm and 75mm x 75mm were chosen. (H/B)cr and (B'/B)cr obtained from series 1 and series 2 respectively for square footing were maintained constant during these tests. Six experiments performed.

Series 4: Effect of Shape of Footing

Four basic footing shapes namely,

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip Footing</td>
<td>75mm x 500mm</td>
</tr>
<tr>
<td>Rectangular Footing</td>
<td>75mm x 150mm</td>
</tr>
<tr>
<td>Square Footing</td>
<td>150mm x 150mm</td>
</tr>
<tr>
<td>Circular Footing</td>
<td>150mm Diameter</td>
</tr>
</tbody>
</table>

Were studied and bearing capacity ratios (BCR) for all the footings were obtained.

Eight experiments performed.
Series 5: Effect of Type of Reinforcement

Three types of reinforcements namely Geotextile, Geogrid-CE 121 and Geogrid-CE 131 were used. The type of footing was rectangular of size 75mm x 150mm.

Twenty Seven experiments performed.

Series 6: Effect of number of reinforcement layers:

The sand layer was reinforced with 1, 2, 3 and 4 layers of geotextile.

Type of footing – Strip footing of size 75mm x 500mm

\[ \frac{H}{B} = 0.8, \quad H=60\text{mm}, \quad B'=5B \]

Five experiments performed.

Series 7: Effect of Surcharge

Surcharge load was applied on the two sides of strip footing in the form of brick layer and concrete cubes.

One brick layer = Surcharge 1.529 kN/m²

Two brick layer = Surcharge 3.06 kN/m²

Concrete cubes = Surcharge 3.60 kN/m²

Four experiments performed.
Analysis of the test results shows that the interpretation of the reinforcing mechanism is highly dependent upon the values assumed for the various model parameters. It was observed that for stiff layer overlying soft layer, failure occurs by the footing punching through the top sand layer, and with full development of the bearing capacity of the lower clay layer. A brief discussion on the analysis of the test results is presented below.

**Series-1: Effect of depth of reinforcement.**

The model test results for Series-1 tests are presented in Table 3.12 to 3.16. The load settlement relationships are shown in Fig.3.3 to 3.7 for strip footing, Fig.3.9 for rectangular footing, Fig.3.11 for square footing and Fig.3.13 for circular footing.

For all the footing shapes, it was observed that for the unreinforced soil system, an increase in the thickness of the sand layer resulted in an increase in the load carrying capacity and a corresponding reduction in settlement of the layered soil. Since there was no definite failure point observed in any of the load-settlement curves, the ultimate bearing capacity was determined by two tangents method. It is also observed that introduction of geotextile layer at the sand-clay interface further improves the performance of footing.

Fig.3.8 shows the variation of ultimate bearing pressure ($q_u$) versus $H/B$ ratios for strip footing, with and without geotextile at the sand-clay interface. The bearing capacity of the layered system increases with the increase in thickness of sand layer up to a certain value of $H/B$. Beyond this value, there is no substantial improvement in the ultimate bearing capacity. The value of $H/B$ at which maximum bearing capacity is achieved is designated as $(H/B)_{cr}$. For strip footing the value of $(H/B)_{cr}$ are 0.8 and 1.4 for reinforced and unreinforced soil system.
respectively. The (H/B)cr values for rectangular footing are 0.8 and 1.20, for square footing are 0.6 and 1.0, and for circular footing are 0.6 and 1.2, respectively.

The observation of the failure surface at the end of the test showed that, at small H/B values the shear failure zones of soil developed below footing extended in to the soft clay sub grade, thus resulting in low bearing capacities. With an increase in fill thickness, an increasing portion of the shear failure zone was developed within granular fill, thus accounting for the improvement in performance. For strip footing when thickness of the fill reached a value of H/B =1.4, the entire shear failure surface was developed and contained within the granular fill layer, at which the bearing capacity reached the maximum value. Therefore, any further increase in fill thickness did not result in any additional improvement in bearing capacity, as the failure surface was always confined within the granular fill layer.

In case of reinforcement at sand-clay interface, at small thickness of sand layer, large deflection developed on the geotextile directly underneath the footing. Since it is generally recognized that a large deflection on the geotextile would mobilize its membrane action and tensile resistance, such mechanisms act to modify the normal stress applied to the sub grade by the combined action of tension in the reinforcement and membrane action in its curvature (Burd 1995). However, when the thickness of sand layer was increased beyond (H/B)cr=0.8, a major portion of the shear failure zone of the soil was observed to develop above the reinforcement layer. This led to ineffective utilization of the membrane action and tensile capacity of the geotextile, and resulted in a gradual reduction of bearing capacity. Finally, when the thickness of sand layer was increased to a value of (H/B) ≥ 1.4, no significant deflection was observed to develop on the reinforcement, and the shear failure zone of the soil was observed to develop well above the reinforcement layer. Therefore, at a fill thickness in excess of H/B=1.4, the system essentially
behaved similar to the unreinforced system, thus the reinforced and unreinforced curves approached each other at \( H/B \geq 1.4 \). Hence, use of geotextile is totally ineffective, when \( H/B \) ratio exceeds 1.4, for strip footing.

**Series 2: Effect of Width of Reinforcement (B')**

To study the effect of width of reinforcement on the performance of the layered soil, tests were conducted with varying widths of reinforcement in relation to footing width (\( B'/B \) ratio) for different shapes of footing. The depth of sand layer was maintained constant equal to (\( H/B \) ) corresponding to a given footing shape as obtained from series 1 test results. In all the tests geotextile was used as reinforcement. The variation of bearing pressure with settlement is shown in Fig.3.15, Fig.3.17, Fig.3.19 and Fig.3.21 for different shapes of footings.

The variation of ultimate bearing capacity with \( B'/B \) ratio for different shapes of footing is shown in Figure 3.23. It is seen that there is a steady increase in ultimate bearing capacity with the increase in the width of reinforcement, up to \( B'/B=5 \) for strip footing, \( B'/B=3.0 \) for rectangular and square footing and \( B'/D=3.0 \) for circular footing. Further increase in the width of reinforcement in excess of critical \( B'/B \) or \( B/D \) ratio, no noticeable improvement in the ultimate bearing capacity is observed. Thus, the results clearly indicate that there is an optimum value for the width of reinforcement at which the maximum bearing capacity can be derived, after which additional area of reinforcement becomes ineffective. This may be due to fact that below the footing there exists a zone of shearing deformation of soil and only that portion of reinforcement which lies within this zone, will have its tensile strength effectively mobilized. Some part of the reinforcement area beyond this zone serves as anchorage to provide pull-out resistance to the geotextile. Hence, an optimum width of reinforcement (\( B' \)), required will be equal to the sum of
length of reinforcement within the shear zone underneath the footing and the length in the anchorage zones on both sides of footing. Any additional length of reinforcement beyond optimum value of B', will be ineffective.

Series 3: Effect of Size of Footing

In order to understand the effect of size of footing, model tests were carried out on both unreinforced and reinforced systems for three different sizes of square footing. The reliability of the model test results can be enhanced for field application if size effects are delineated. As mentioned earlier (H/B)cr=0.6 and (B'/B)cr=3.0 were maintained constant for square footing. The bearing pressure-settlement results are shown in Table-3.21, 3.22 and 3.23.

The bearing pressure-settlement relationships for all three footing sizes are shown in Fig.3.24, 3.25 and Fig.3.26. It is evident from the figure that bearing capacity increases with increase in the size of footing, for both reinforced and unreinforced systems. The bearing capacity ratio (BCR) is observed to be nearly same for all the three sizes. This indicates that percentage improvement in bearing capacity as shown by small scale model footing tests on reinforced soil beds may not change much for prototype footings in the field. Thus, the effect of size of footing on bearing capacity is not significant.

Series 4: Effect of Shape of Footing

Four basic shapes of footings with their BCR are shown in Table 3.24. The type of reinforcement used was geotextile, while the values of (H/B)cr and (B'/B)cr were kept constant corresponding to their optimum values. The pressure settlement relationships for both reinforced and unreinforced cases are shown in Fig.3.28 to Fig.3.32.
It was observed that for a footing of given shape, the ultimate bearing capacity is considerably higher for a reinforced system, and at any given load, corresponding settlements are much smaller as compared to the unreinforced system. It is evident from the test results that percentage improvement in bearing capacity (BCR) is almost same for all the four basic footing shapes. This is in contrast to behavior in respect of unreinforced case. The shape factor which has different values depending upon the footing shape in case of unreinforced soil e.g. 0.5 for strip, 0.4 for square and 0.3 for circular (Bowles, 1976), tends to a near constant value for footings on reinforced soil. This is due to a larger effective volume of soil that is involved in the reinforced case, which masks the shape effect.

Fig.3.33 shows the variation of BCR with percentage settlement(S/B) %, for all the four footing shapes. The bearing capacity ratios for all the four shapes of footing are nearly equal.

**Series 5: Effect of Type of Reinforcement**

The effect of type of reinforcement on ultimate bearing capacity was studied using three types of reinforcements. The results are reported in Table-3.29, 3.30 and 3.31.

Figure 3.34 shows the variation of BCR with H/B for rectangular footing of size 75 mm x 75 mm for three types of geosynthetics namely, Geotextile, Geogrid 1 (Netlon CE 121) and Geogrid 2 (Netlon CE 131). It is seen that Geotextile yields the maximum value of bearing capacity ratio (BCR) which is approximately 16 % and 21 % greater than BCR values obtained for Geogrid CE 121 and Geogrid CE 131 respectively at (H/B)cr.

The model test results clearly indicate that geotextile is most effective in terms of improvement in bearing capacity as compared to the geogrids. The superior performance of the geotextile may be attributed to its higher tensile strength compared to the geogrids. Moreover, due to hexagonal
apertures present in the geogrid, there are chances for the soft clay subgrade to extrude through the geogrid apertures, weakening the bond between the geogrid and the granular layer. On the other hand, the geotextile is in plane sheet form acts as a separator between the clay subgrade and granular fill and thus the contribution of membrane forces is more significant in addition to the reinforcing action. Thus, geotextile gives better performance than geogrids especially on soft clay subgrade.

As seen from Fig.3.34, geogrid CE 121 having aperture size 8 mm x 8 mm, yields higher BCR than geogrid CE 131 having aperture size 27 mm x 27 mm. This may be due to higher tensile strength and smaller aperture size of geogrid CE 121 as compared to geogrid CE 131. The larger aperture size of geogrid CE 131 provides lesser lateral bearing area for the top granular fill giving poor performance as compared to geogrid CE 121.

**Series 6: Effect of number of reinforcing layers**

In order to study the effect of number of reinforcing layers, geotextile was used as a reinforcing material with strip footing. (B'/B)=5 and (H/B) =0.8 were maintained constant for all the tests. The vertical spacing of reinforcing layers in terms of Z/B ratio was kept 0.20 for all the tests.

The test results are reported in Table-3.32.

As seen from pressure-settlement relationships (Fig.3.36), the ultimate bearing capacity of strip footing increases with increase in the number of reinforcing layers up to 3, beyond which there is no remarkable improvement in the ultimate bearing capacity. When three layers of geotextile were provided, the ultimate bearing capacity was increased by 43.7 % and settlement was reduced by 15.7%.
Fig. 3.37 shows a plot of ultimate bearing capacity ($q_u$) versus number of reinforcing layers ($N$).

**Series 7: Effect of Surcharge**

To study the effect of surcharge on the ultimate bearing capacity of reinforced soil mass, uniform surcharge load was applied on each side of the strip footing up to width equal to the width of reinforcement $B'(5B)$. The surcharge load was applied in the form of one brick layer, two brick layer, and a layer of concrete cubes.

The results are reported in Table-3.33 and Fig.3.38. As seen from the results, the ultimate bearing capacity ($q_u$) of reinforced soil mass was further increased by 10% when an uniform surcharge of 3.60 kN/m$^2$ was applied on either side of the footing.

The increase in bearing capacity due to application of surcharge is attributed to the increase in the tension in the reinforcement.

When a granular bed of thickness $H$, of bulk density, $\gamma_s$ and friction angle $\phi_s$ with reinforcement is provided over soft soil, the bearing capacity of the footing resting on this foundation medium is increased. Frictional forces developed between the soil and the reinforcement induces tensile strains in the reinforcement. The tensile strains developed provide the confining effect. This will induce additional shearing resistance along the vertical plane at the edge. Thus, the ultimate bearing capacity of the sand overlying soft clay with geotextile reinforcement at the sand-clay interface comprises of the contribution from stress distribution ($q_d$), contribution due to shear layer effect ($q_s$), and the contribution due to membrane action ($q_m$).

$$q_u = q_d + q_s + q_m \quad \text{------------------ (1)}$$
(a) Contribution to bearing capacity from stress distribution (qd):

From Fig.4.2 it can be seen that the contribution to the bearing capacity from stress distribution through the upper sand layer, qd is:

\[ qd = qc \cdot \frac{Br'}{B} \quad \text{kN/m}^2 \]

\[ qd = Cu \cdot Ne \cdot \frac{Br'}{B} \quad \text{--- (2)} \]

(b) Contribution to Bearing Capacity due to Shear Layer Effect:

Frictional forces developed between the granular soil and the reinforcement induces tensile strains in the reinforcement. The tensile strains developed provide the confining effect. This will induce additional shearing resistance along the vertical plane at the edge of footing, known as the shear layer effect. (Shivshankar, 1993).

\[ qs = \text{Contribution to bearing capacity due to shear layer effect} \]

\[ = Kp \cdot \gamma s \cdot H^2 \cdot \tan \theta s \cdot \frac{1}{B} \quad \text{--- (3)} \]

(c) Contribution to Bearing Capacity due to Membrane Action of Reinforcement (qm):

\[ qm = \text{Contribution to Bearing Capacity due to membrane action} \]

\[ = 2 \cdot \gamma s \cdot H \cdot B \cdot \tan \theta r \cdot L_e \cdot \tan \theta s \quad \text{--- (4)} \]

Now, we have

\[ qu = qd + qs + qm \]

\[ = Cu \cdot Ne \cdot \frac{Br'}{B} + Kp \cdot \gamma s \cdot H^2 \cdot \tan \theta s \cdot \frac{1}{B} + 2 \cdot \gamma s \cdot H \cdot B \cdot \tan \theta r \cdot L_e \cdot \tan \theta s \quad \text{--- (5)} \]