Relative Settlement of Strip Footing on Sand Mat overlying Thick Soft Clay

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ABSTRACT: Shallow foundations in plot having soft soils deposit can undergo a compression after consolidation and secondary settlement. For low to medium rise building projects on soft soil condition, a deep foundation may not be feasible for high cost. In such cases an alternative to deep foundations may be shallow strip footings placed on a double layer foundation system in which the untreated or cement treated compacted sand is upper layer to reduce the settlement to a permissible level. This research study deals with the bearing capacity of a rigid plane-strain footing placed on the surface of a soil consisting of an untreated or cement treated sand layer overlying a thicksoft clay. The study considered both the thin or thick sand layer is compared to the footing width. The response of the clay layer is undrained for elasto-plastic loading stages and drained in consolidation stages is considered. The settlement of the shallow strip foundation resting on mentioned layered soils system has been analyzed. Parametric study has been conducted to determine the effect of thickness, density, cementation of sand mat and shear strength of the soft clay layer on the settlement of shallow strip foundation. A better insight of elasto-plastic, consolidation and creep settlements of the footing on sand mat under different footing pressure has been developed. This may be a guidelinefor designing shallow strip footing on sand mat over thick soft clay.

The relative settlement (S/S₀) at the center point of the footing for both untreated or cement treated upper sand mat was calculated, where S₀ is the settlement for the case with H₀= 0.25m and S is the settlement for other thickness of upper sand mat. A larger value of relative settlement S/S₀ indicates larger difference of settlement between the cases of small and larger thickness of sand layer. From this study it is concluded that the relative settlement S/S₀may be considered as the index of the effectiveness of sand layer.Brittle behavior of cemented sand and fracture or cracks is not considered in this analysis.

Keywords—Ground improvement, PLAXIS 2D, primary and secondary settlement, relative settlement, sand Mat, soft clay.

I. INTRODUCTION

The bearing capacity of a shallow footing on a homogeneous soil may be estimated shortly using conventional bearing capacity theory in which appropriate bearing capacity factors are adopted assumption that the soil is rigid-perfectly plastic with the strength characterized by cohesion and angle of friction. This approach cannot, in general, be used for cases where the soil properties arevariable with depth. At first design charts for ultimate bearing capacity for sands overlying clay was developed by [1]. Design guideline for cement treated soil overlying clay was developed by [2]. If a foundation is placed on the surface of a layered soil, and if the thickness of the top layer is comparable to the foundation width, then this approach may not be appropriate.

This research attempts to Investigate and quantify the effect of dense sand mat on soft soil on the settlement and deformation pattern or strain field of strip footings on underlying layered soil. The study considered both the cases where the thickness of the sand layer is thin or thick compared to the width of footing. The response of the clay layer is undrained for elasto-plastic loading stages and drained in consolidation stages is considered. A parametric study has been conducted to determine the effect of thickness, density, cementation of sand mat and shear strength of the soft clay layer on the settlement of shallow strip foundation. An insight is developed to study the effectiveness of sand mat for different material characteristics to avoid punching shear failure and to limit the settlement to a permissible level.
II SELECTION OF SOIL PROPERTIES FOR THIS STUDY

Sub-soil Characteristics in different regions of Bangladesh has been used as obtained from previous literature reviewed by us. Inorganic Soft Clay Soils different parts of Bangladesh and sand of Dhaka and Major River bed of Bangladesh has been reviewed by us[3]-[5]& [8]. For inorganic clay of Bangladesh generally the value of Liquid Limit (LL) is below exceed 60% and Plasticity Index (PI) below 30%. LL=60% and PI=30% has been selected for this research[3]& [8]. For Normally consolidated clay: $E_u^{50} = \frac{45000 \cdot C_u}{t_{\gamma_d}}$ [6]. According to PLAXIS manual, $E_u$ of soft soil may be converted into $E'$ by: $E' = \frac{2(1+v')}{3} E_u$ where $v' \leq 0.35$[6]. From literature presented by [2]&[8] for soft high plastic (CH) clay, $c_i = 12$ kPa, $E_u^{50} = 6000$ kPa and $E' = 5000$ kPa have been used.

Correlation between drained shear strength and plasticity index of NC clay is $\phi_{NC} = 43 - 10 \log PI$ (deg) has been used according to[9]. For PI=30% this correlation gives $\phi_{NC} = 28^\circ$. A value of 24$^\circ$ for Bangladeshi soft clay has been used in this analysis.[3]. As PLAXIS does not allow a zero value of drained cohesion and for that a unit value 1.0 kPa for these parameters have been used instead of zero.

According to data obtained by [3] an average value of Dry Density $\gamma_d$=14.70 kN/m$^3$ and the relationship, $\gamma_{sat} = \gamma_d + \frac{\gamma_w}{1+e}$ an average value of Saturated Unit Weight 20 kN/m$^3$ was taken for this study. According to [3] & [8] correlation for $C_{NC}$ of Plastic Silt and Clay of different area of Bangladesh is, $C_{NC} = 0.0078(LL-14)$. According to the correlation for $LL=60\%$, $C_{NC}$ near to 0.35. However, a zero value of $C_{NC}$ is not allowed by PLAXIS and for this reason a very small value of $C_{NC} = 0.001$ has been used instead of zero. According to[4] the void ratio for inorganic soft clay of Bangladesh is as large as 1.463. Liquid limit is the mineralogical properties of a soil while the void ratio is a measure of density and may vary keeping the liquid limit fixed. Four different value of void ratio 1.00, 1.15, 1.30 and 1.45 has been used.

The literature related to properties of cement stabilization of sands has been reviewed and parameters of cement treated sand required for the present analysis have been selected from those found from literature review. For coarse-grained soils, a relationship found between cement content (by weight), $C$ and unconfined compressive strength $f_c$ for cement treated soils obtained by [10] which is $f_c = 150C$ for 90 days curing time and 413.64 kPa (60 psi) confining pressure. According to same study cement treatment leads to an increase in cohesive strength and the increase in cohesion is: $c(PSI) = 7.0 + 0.225\sigma_c$, where, $\sigma_c$ is unconfined compressive strength (psi) and $c$ is effective cohesion. In a given range of stresses, shear strength of cemented sands can be represented by straight Mohr-Coulomb envelopes defined by $c$ as a unique function of cementation, and $\phi$, which seems to be not affected by the cement content. Cemented soils show a very stiff behavior before yielding. The brittle behavior changes to a ductile soil response as the stress level changes from low to high. Basically, it comprises an initial stiff behavior followed by increasingly plastic deformation approaching failure. The brittle response of cemented soil increases with increasing cement content and decreases as the initial mean effective stress increases and the axial strain at failure decreases with increasing cement content and decreasing initial mean effective stresses.

III SUB SOIL SYSTEM AND MATERIAL PROPERTIES DATA

![Soil Layer Diagram]

**Sand Layer (Either Uncemented or Cemented)**
$c=1$, $\phi=24^\circ$, $\gamma_{sat} = 20kN/m^3$

**Clay Layer**
$c=1$, $\phi=28^\circ$, $\gamma_{sat} = 20kN/m^3$
Figure 1.0. Schematic diagram of the problem.
The subsoil and strip footing system has been considered as a two layer system. The top layer is a sand layer of thickness \(H\) and the bottom layer is a homogenous soft clay layer with effective shear strength parameters \(c’\) and \(\phi’\). The footing width \(B=2.5\) m and this is placed on the sand layer. The length of the finite element model is \(7B\) and the depth of clay layer is \(6B\) has been taken as sufficiently large to avoid boundary effect so that there will be no deformation of ground at the model boundary due to footing pressure.
The bearing capacity of soil depends on strength parameters \(c’\), \(\phi’\). The soils were modeled with three material models-Hardening Soil (HS) Model, Soft Soil (SS) Model and Soft Soil Creep (SSC) Model according to previous literatures [6] & [7]. The HS model is used to simulate the untreated and cement treated sand layer and the SS and SSC model is used to simulate soft clay layer. The input parameters used in different models are represented in Table 1.0 & Table 2.0.

**Table 1.0. Material set input parameters for the lower clay layer**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Material Set</th>
<th>Clay</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elastoplastic Stage</td>
<td>Consolidation Stage</td>
<td>Creep Stage</td>
</tr>
<tr>
<td>Material model</td>
<td>HS</td>
<td>SS</td>
<td>SSC</td>
</tr>
<tr>
<td>Drainage Condition</td>
<td>U</td>
<td>U</td>
<td>D</td>
</tr>
<tr>
<td>Poisson's Ratio, (\nu’)</td>
<td>0.2</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Saturated Unit Weight (below phreatic level), (\gamma_s)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Unsaturated Unit Weight (above phreatic level), (\gamma_u)</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Drained Cohesion, (c_{ref})</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Drained Friction Angle, (\phi’)</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Dilatancy Angle, (\mu’)</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Initial Stress, (K_{\phi=1-sin\phi'})</td>
<td>0.593</td>
<td>0.593</td>
<td>0.593</td>
</tr>
<tr>
<td>OCR</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Interface Reduction Factor, (R_{inter})</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Horizontal Permeability, (k_h)</td>
<td>1.0E-4</td>
<td>1.0E-4</td>
<td>1.0E-4</td>
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<tr>
<td>Vertical Permeability, (k_v)</td>
<td>1.0E-4</td>
<td>1.0E-4</td>
<td>1.0E-4</td>
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<td>Triaxial Stiffness, (E_{50}^{ref})</td>
<td>5000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Oedometer Stiffness, (E_{o}^{total})</td>
<td>4750</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Unloading/Reloading Stiffness, (E_{ur}^{ref})</td>
<td>15000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power, (m) (Required for HS Model)</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Compression Index, (C_c)</td>
<td>-</td>
<td>0.36</td>
<td>0.36</td>
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<tr>
<td>Swelling Index, (C_s)</td>
<td>-</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Creep Index, (C_u)</td>
<td>-</td>
<td>-</td>
<td>0.018</td>
</tr>
<tr>
<td>Natural Void Ratio, (e_{pul})</td>
<td>1.00,1.15,1.30,1.45</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

U - Undrained and D - Drained

**Table 2.0. Material parameters for the Concrete Strip Footing**

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Parameter Value</th>
<th>Unit</th>
<th>Input Parameter</th>
<th>Parameter Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Type</td>
<td>Plate</td>
<td>-</td>
<td>Flexural Rigidity, (EI)</td>
<td>1.35E+06</td>
<td>kNm²/m</td>
</tr>
<tr>
<td>Material Model</td>
<td>Elastic</td>
<td>-</td>
<td>Equivalent Thickness, (d)</td>
<td>0.60</td>
<td>m</td>
</tr>
<tr>
<td>Drainage Condition</td>
<td>Undrained</td>
<td>-</td>
<td>Poisson's Ratio, (\nu’)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Normal Stiffness, (EA)</td>
<td>4.5E+07</td>
<td>kN/m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**IV NUMERICAL ANALYSIS IN PLAXIS**

While a three-dimensional finite element analysis is frequently used in structural or mechanical applications, it is rarely used in geotechnical problems. A plane strain finite element model has been used to carry out current two-dimensional finite element analyses. Elongated shallow footing which support load bearing walls...
or a single row of columns are generally referred to a strip footing. The characteristic feature of a Plane Strain 2D Analysis is the dimension along the z-axis is considerably very large compared with the other two dimensions. Loads and boundary conditions are independent of the largest dimension and the strains in the direction of z-axis are considered to be zero. Finite Element Analysisof the strip footing on double layered soil using PLAXIS 2D is done including general settings of model geometry, standard fixities and15-node triangular element having 12 stress points i.e. gaussian integration points is used in current analysis. The type of element for structural and interfaces elements is automatically taken to be compatible with the selected type of element for adjacent soil. The 15-node triangle is a very accurate element that has produced high quality stress results for complex problems. The plate elements are composed of beam elements having three degrees of freedom per node. A plate element has five nodes if used with 15 noded soil elements. The plate element has been selected “elastic” for all the cases to simplify the calculations and is in accordance with the reality, since strip footings are designed to have an elastic response. Interface elements are used to simulate the interaction between two materials. The boundary type restricts both horizontal and vertical displacements to zero at the bottom boundary and horizontal displacements to zero at the side boundaries. An unstructured mesh with elements and the initial water pressure is generated from the phreatic level. In the consolidation analysis, closed consolidation boundary has been used at the left and right side of the geometry and the bottom horizontal boundary is automatically closed consolidation boundary with the top of the geometry is kept open for consolidation.

When the material is granular and the pore pressures dissipate quickly relative to the speed of loading, the added load is carried by the soil skeleton and not pore pressures. This situation is drained and effective stresses has been used in the analysis. On the other hand during loading a saturated material that allowing no pore water to dissipate quickly compared to the speed of loading, the load will be carried by the pore pressures rather than the soil skeleton and the situation is undrained analysis. Material data set has been reassigned to soil clusters to simulate its appropriate condition in different phases during various construction stages. Automatic load stepping and load advancement was allowed and additional load step was needed.

Fig.2.0 PLAXIS Model Geometry.

V 2D MODELING OF STRIP FOOTING ON SAND LAYER OVER CLAY DEPOSIT

During the modeling in PLAXIS 2D, a natural clay deposit of 15m thickness and 18m width has been used. A untreated or cement treated dense sand layer of varying thickness is considered over the natural clay deposit.

A 2.5m wide concrete strip footing is installed at the center of top surface of the sand layer (Figure 2.0). Ground water level is at top level of clay deposit that make this fully saturated. Uniformly distributed vertical load of varying value is applied to the strip footing and lots of analysis of this soil and foundation system has been carried out using PLAXIS 8.0 for the primary and secondary settlement.
Distributed load has been applied only in y-direction. Loads were activated firstly in the second plastic calculations phase and secondly in the creep calculations phase. Only the effective soil parameters are used in both types of material drained or undrained. A Poisson’s coefficient (ν) of 0.3 has been used, which is suitable for drained conditions and alternative stiffness parameters are automatically calculated from the Young modulus and the Poisson’s ratio.

Fig.3.0 Finite element mesh for the geometry model.

Plate properties parameters have been given in Table 2.0. For thin and flexible structures a Poisson’s coefficient (ν) of value of zero and strip footing has been modeled through the plate element. Then generated Fine mesh has been provided by refinement at surrounding location of footing plate for better accuracy of results and the coarseness has been increased gradually at distant location (Figure 3.0). The initial stress-state was calculated with the K₀-procedure (Jaky’s formula, \( K_0 = 1 - \sin \phi \) and proper OCR) and the initial water condition was calculated by the phreatic level. The calculation was performed as a plastic and consolidation calculation and the ’Updated mesh analysis’ has been chosen for all phases, as large deformations were expected. ’Updated water pressure analysis’ has been used for lowering of water head. Period of secondary compression is 10-30 years. ‘Ignore undrained behavior’ has not been selected with K₀-procedure. PLAXIS distinguishes between drained and undrained soils to model permeable sands as well as almost impermeable clays. Excess pore pressures are computed during plastic calculations when undrained soil layers are subjected to loads.

Each calculation is carried out with an initial phase and three subsequent phases which are described below:
Phase 1: Strip foundation on a sand mat underlain by natural clay deposit. In this phase the lower layer is ‘Undrained Clay’ (SS Model) and the upper layer is Drained Sand or Undrained Cemented Sand (HS Model). Strip footing plate and load is activated in this phase. Elastoplastic deformation of the problem geometry under assigned load is calculated in this phase.
Phase 2: The lower layer is ‘Undrained Clay’ (SS Model) and the upper layer is ‘Drained Sand’ or ‘Undrained Cemented Sand’ (HS Model). No additional load is activated in this phase. Deformation of the problem geometry due to consolidation under the load applied at ‘Phase 1’ is calculated in this phase. The consolidation settlement occurred in this phase through dissipation of pore water pressure up to a very small value which is 1.0kN/m².
Phase 3: The lower layer is ‘Undrained Clay’ (SSC Model) and the upper layer is same as ‘Phase 2’. No additional load is activated in this phase. After about full dissipation of pore water pressure inter particle rearrangement or creep is occurred without application of any additional load. Creep deformation of the problem geometry under load applied at ‘Phase 2’ is calculated in this phase.

**VI PARAMETRIC STUDY**
The load that causes bearing capacity failure (soil body collapse) of surface footing is less than that for footing embedded into ground. Consolidation settlement of surface footing is more than that of embedded footing under the same load. Elasto-plastic Settlement obtained from PLAXIS analysis is 61–87% of calculated values of
these from classical settlement theory. Consolidation Settlement obtained from PLAXIS analysis is 64-66% of calculated values of these from classical consolidation theory.

From each analysis total vertical settlement at footing center and deformation of the subsoil was obtained from 2D PLAXIS analyses. Footing width, B is kept constant for all the analysis done in this study. The dimensionless forms for a wide range of values are used to generalize their effect. Here, \( H/B \) is the non-dimensional layer thickness, \( q/ \gamma \) sat \( B \) is the non-dimensional loads on strip footings. \( c \) and \( \phi \) of soft clay and \( \phi \) of sand mat are also kept constant for all the analysis done in this study and the value of \( q/ \gamma \) sat \( H \) was varied.

Analysis was done for different footing pressure \( q \), vertical settlement \( S \) and void ratio \( e \) ini for different thickness of upper sand mat layer, \( H \). The values of \( e \) ini are 1.0, 1.15, 1.3, 1.45, values of \( H \) (m) are 0.75, 1.0, 1.25, 1.5, 1.75, 2.0 and \( q \) (kN/m²) are 50, 75, 100, 125, 150, 175, 200 used in analysis which are similar to founding pressure of three to eight storied residential or commercial buildings. The values of relative depth \( H/B \) used are 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 and normalizes footing pressure \( q/ \gamma \) sat \( B \) used are 1, 1.5, 2.5, 3, 3.5 and 4. Settlement (downward vertical displacement) of footing center (midpoint of footing plate) is denoted as \( S \) when \( H \) (m)=0.75, 1.0, 1.25, 1.5, 1.75 and 2.0m. Analyses were conducted by changes of the thickness of upper sand layer from 0.25 to 2.00m.

Settlement at midpoint of footing plate when \( H = 0.25 \)m is \( S_0 \). It was tried to analyze the current problem without any sand mat and in this case bearing capacity failure occurred before completion of application of total load. Hence, a small thickness of upper sand layer equal to 0.25m has been used which is the minimum thickness to avoid soil body collapses during application of total amount of load in a PLAXIS analysis and to get the total settlement due to that load. Sand layer thickness, \( H = 0.75 \)m or more has been used for improvement purpose of the ground. It may be noted that both \( S_0 \) and \( S \) changes when footing pressure changes. Settlement of the footing on improved ground is \( S \) and this is always less than \( S_0 \). So that, \( S/S_0 < 1.0 \). This is the definition and significance of the term relative settlement, \( S/S_0 \) introduced by this research.

VII RESULTS FOR UNTREATED SAND AS UPPER LAYER

Variations of \( S/S_0 \) with \( q/ \gamma \) sat \( B \) for different \( e \) ini is presented in Fig. 4 as plots of \( S/S_0 \) (the relative settlement) against \( q/ \gamma \) sat \( B \), \( e \) ini and \( H \). Effect of initial void ratio on the relative settlement is not significant. The difference of relative settlement for different normalized footing pressure remains more or less same for different value of relative thickness of upper sand mat at right zone. For a given \( H/B \), with a given increase in \( S_0 \), higher compared to the increase in \( S \). As a result \( S/S_0 \) decreased. Stated in a different way, a larger relative settlement means that the sand mat is more effective in controlling the settlement. For a given thickness of sand mat and clay layer, the effectiveness of the sand mat reduces with increase of footing pressure and after a certain value of footing pressure the sand mat appears to be no longer effective. For a given \( H \) as \( q/ \gamma \) sat \( B \) is increased up to a value of 2.5 the relative settlement decreases indicating the effectiveness of the sand layer in settlement reduction. \( S/S_0 \) may be considered as the index for the effectiveness of the sand layer. Variation of \( S/S_0 \) with \( H \)/\( B \) for different \( q/ \gamma \) sat \( B \) presented in figures 5.1 to 5.4.

![Fig. 4 Variation of S/S₀ with q/γ sat B for different e ini at H/B=0.60](image-url)
Fig. 5.1 Variation of $S/S_0$ with $H_i/B$ for different $q/\gamma_{sat}B$ at $e_{ini}=1.0$

Fig. 5.2 Variation of $S/S_0$ with $H_i/B$ for different $q/\gamma_{sat}B$ at $e_{ini}=1.15$

Fig. 5.3 Variation of $S/S_0$ with $H_i/B$ for different $q/\gamma_{sat}B$ at $e_{ini}=1.3$
Fig. 5.4 Variation of $S/S_0$ with $H/H/\beta$ for different $q/\gamma_{\text{sat}}B$ at $e_{\text{init}}=1.45$

Fig. 6.1 Variation of $S/S_0$ with $q/\gamma_{\text{sat}}B$ for different $H/H/\beta$ at $e_{\text{init}}=1.0$

Fig. 6.2 Variation of $S/S_0$ with $q/\gamma_{\text{sat}}B$ for different $H/H/\beta$ at $e_{\text{init}}=1.15$
For a particular value of normalized footing pressure, $q/\gamma_{sat}B$, $S_0$ is same and therefore decrease of $S_0/S$ implies decrease of settlement, $S$. Thus, reduction in $S_0/S$ with increase in $H_i/B$ for a given $q/\gamma_{sat}B$ indicates better settlement control (reduction) by the sand mat. It can be observed that for all value of $e_{init}$, $S_0/S$ decreases with increase of normalized value of thickness of upper sand layer, i.e. $H_i/B$. For a value of $q/\gamma_{sat}B$ $\leq 0.6$, increase of $S_0/S$ with $q/\gamma_{sat}B$ is more significant for values of $q/\gamma_{sat}B$ equal to 2.5 and above. On the other hand for $H_i/B > 0.6$, there is little change of $S_0/S$ with $q/\gamma_{sat}B$. For values of $q/\gamma_{sat}B < 2.5$, changes in $S_0/S$ for different $q/\gamma_{sat}B$ are small for any $H_i/B$.

For a particular value of normalized footing pressure, $q/\gamma_{sat}B$, $S_0$ is same and therefore decrease of $S_0/S$ implies decrease of settlement, $S$. Thus, reduction in $S_0/S$ with increase in $H_i/B$ for a given $q/\gamma_{sat}B$ indicates better settlement control (reduction) by the sand mat. It can be observed that for all value of $e_{init}$, $S_0/S$ decreases with increase of normalized value of thickness of upper sand layer, i.e. $H_i/B$ for a particular $q/\gamma_{sat}B$. For a value of $H_i/B \leq 0.6$, increase of $S_0/S$ with $q/\gamma_{sat}B$ is more significant for values of $q/\gamma_{sat}B$ equal to 2.5 and above. On the other hand for $H_i/B > 0.6$, there is little change of $S_0/S$ with $q/\gamma_{sat}B$. For values of $q/\gamma_{sat}B < 2.5$, changes in $S_0/S$ for different $q/\gamma_{sat}B$ are small for any $H_i/B$.

Variation of $S_0/S$ with $q/\gamma_{sat}B$ for different $H_i/B$ at a given void ratio $e_{init}$ is presented in Fig. 6.1 through 6.4. It is observed that, for all value of $e_{init}$, $S_0/S$ decreases with increase of different $q/\gamma_{sat}B$ for normalized value of thickness of upper sand layer $H_i/B$. The relative settlement decreases at a high rate with the increase of thickness of upper sand layer $H_i/B$ upto $q/\gamma_{sat}B=2.5$. After this particular value of footing pressure, this rate of decrease of relative settlement is smaller. For a particular value of $H_i/B$, decrease of $S_0/S$ with $q/\gamma_{sat}B$ is more significant for value of $q/\gamma_{sat}B<2.5$. For values of $q/\gamma_{sat}B>2.5$, $S_0/S$ at different $q/\gamma_{sat}B$ are quite closer.

IX RESULTS FOR CEMENT TREATED SAND AS UPPER LAYER

Variation of $S_0/S$ with $q/\gamma_{sat}B$ for different $e_{init}$ is presented in Fig. 7 shows that for a single thickness of upper sand layer, $S_0/S$ decreases with increase of $q/\gamma_{sat}B$ for different value of $e_{init}$. This decreasing rate (slope) is not constant for all $q/\gamma_{sat}B$. It is observed for Fig. 7 that the relative settlement decreases at a high rate with the increase of normalized footing pressure upto a certain value of normalized footing pressure. After this particular value of normalized footing pressure, this rate of decrease of relative settlement is smaller. In general three distinct zones can be identified in the relationship of $S_0/S$ vs $q/\gamma_{sat}B$ for different $e_{init}$. At left zone up to $q/\gamma_{sat}B=2.5$ the $S_0/S$ decreases rapidly and at middle zone from $q/\gamma_{sat}B=2.5–3.5,$ $S_0/S$ rate of decrease of $S_0/S$ is low and at right zone for
For a given thickness of sand mat and clay layer, the effectiveness of the sand mat reduces with increase of footing pressure and after a certain value of normalized footing pressure 3.5 the sand mat appears to be no longer effective. Similar observation can be made for all other thickness (0.75m–2.0m) of sand layer.

For a given \( H_i/B \) if the \( q/\gamma_{sat}B \) is increased up to a value of 2.5 the relative settlement \( S/S_0 \) decreases indicates increasing effectiveness of the sand layer in reducing the settlement. However, beyond the value of \( q/\gamma_{sat}B=2.5 \), there is little reduction in relative settlement.

Variation of \( S/S_0 \) with \( H_i/B \) for different \( q/\gamma_{sat}B \) and for different void ratios is presented in figures 8.1 to 8.4. For a particular normalized footing pressure, \( q/\gamma_{sat}B \), \( S_0 \) is same and therefore decrease of relative settlement, \( S/S_0 \) implies decrease of settlement, \( S \). Reduction in \( S/S_0 \) with increase in \( H_i/B \) for a given \( q/\gamma_{sat}B \) indicates better settlement control (reduction) by the sand mat. It can be observed from these graphs that for all value of \( e_{init} \), \( S/S_0 \) decreases with increase of normalized value of thickness of upper sand layer \( i.e., H_i/B \) for a particular \( q/\gamma_{sat}B \). For a value of \( H_i/B \leq 0.6 \), increase of \( S/S_0 \) with \( q/\gamma_{sat}B \) is more significant for values of \( q/\gamma_{sat}B \) equal to 2.5 and above. On the other hand for \( H_i/B > 0.6 \), there is little change of \( S/S_0 \) with \( q/\gamma_{sat}B \). For values of \( q/\gamma_{sat}B < 2.5 \), changes in \( S/S_0 \) for different \( q/\gamma_{sat}B \) are small for any \( H_i/B \).
Fig. 8.2 Variation of $S/S_0$ with $H_i/B$ for different $q/\gamma_{sat}B$ at $e_{init}=1.15$

Fig. 8.3 Variation of $S/S_0$ with $H_i/B$ for different $q/\gamma_{sat}B$ at $e_{init}=1.30$

Fig. 8.4 Variation of $S/S_0$ with $H_i/B$ for different $q/\gamma_{sat}B$ at $e_{init}=1.45$
Fig. 9.1 Variation of $S/S_0$ with $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init} = 1.00$

Fig. 9.2 Variation of $S/S_0$ with $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init} = 1.15$

Fig. 9.3 Variation of $S/S_0$ with $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init} = 1.30$
Variation of $S/S_0$ with $q/\gamma_{sat}B$ for different $H_i/B$ is presented in Fig. 9.1 through 9.4 presents the effect of $q/\gamma_{sat}B$ on $S/S_0$ for various $H_i/B$ and at a given $e_{init}$. It is observed that for all value of $e_{init}$, $S/S_0$ decreases with increase of different $q/\gamma_{sat}B$ for normalized value of thickness of upper sand layer $H_i/B$. It is observed that the $S/S_0$ decreases at a high rate with the increase of thickness of upper sand layer $H_i/B = 2.5$. After this particular value of footing pressure, this rate of decrease of $S/S_0$ is smaller. For a particular value of $H_i/B$, decrease of $S/S_0$ with $q/\gamma_{sat}B$ is more significant for value of $q/\gamma_{sat}B < 2.5$. For values of $q/\gamma_{sat}B > 2.5$, $S/S_0$ at different $q/\gamma_{sat}B$ are quite closer.

X COMPARISON BETWEEN EFFECTIVENESS OF UNTREATED AND CEMENT TREATED SAND LAYER

The effectiveness of Untreated and Cement Treated Sand upper layer is compared in this section. For $e_{init} = 1.0$ the effectiveness of untreated upper sand layer and cement treated upper sand layer is presented in Fig. 10.1 and Fig. 10.2 as variation of $S/S_0$ with $q/\gamma_{sat}B$ for different Sand Type at different $H_i/B$.

From Fig. 9.1 through 9.4 it is observed that for $q/\gamma_{sat}B < 2.5$ the cement treated upper sand layer is more effective than untreated upper sand layer in reducing $S/S_0$ and for $q/\gamma_{sat}B > 2.5$ the effectiveness of untreated upper sand layer and cement treated upper sand layer is about similar in reducing relative settlement $S/S_0$.
For \( e_{\text{sat}} = 1.0 \) the effectiveness of untreated upper sand layer and cement treated upper sand layer is presented in Fig. 11.1 and 11.2 as variation of \( S/S_0 \) with \( H_i/B \) for different Sand Type at different \( q/\gamma_{\text{sat},1}B \). It is observed that for \( H_i/B < 0.5 \) the cement treated upper sand layer is more effective than untreated upper sand layer in reducing relative settlement \( S/S_0 \) and for \( H_i/B > 0.5 \) the effectiveness of untreated upper sand layer and cement treated upper sand layer is about similar in reducing relative settlement \( S/S_0 \).
XI SIGNIFICANCE OF RELATIVE SETTLEMENT $S/S_0$

Thus a higher value of $S/S_0$ implies larger difference between $S$ and $S_0$. Stated in a different way a larger relative settlement means that the sand mat is more effective in controlling the settlement. For a given thickness of sand mat and clay layer, the effectiveness of the sand mat reduces with increase of footing pressure and after a certain value of footing pressure the sand mat appears to be no longer effective. Similar observation can be made for both untreated or cement treated upper sand layer.

The relative settlement decreases at a high rate with the increase of normalized footing pressure up to a certain value of normalized footing pressure for both untreated or cement treated upper sand layer. In general three distinct zones can be identified in the relationship of $S/S_0$ vs $q/\gamma_{sat}$ for different $e_{min}$. At left zone up to $q/\gamma_{sat}=2.5$ the $S/S_0$ decreases rapidly and at middle zone from $q/\gamma_{sat}=2.5$ to 3.5 the $S/S_0$ decreases, decreasing rate of $S/S_0$ is low and at right zone for $q/\gamma_{sat}>3.5$ there is no decrease of $S/S_0$. That is sand mat is no longer effective to reduce settlement at $q/\gamma_{sat}>3.5$. The difference of relative settlement for different normalized footing pressure remains more or less same for different value of relative thickness of upper sand mat at right zone. The relative settlement decreases for a given $H$ if the $q/\gamma_{sat}$ is increased up to a certain value of 2.5 means the effectiveness of the sand layer in controlling settlement reduces for both untreated or cement treated upper sand layer. $S/S_0$ may be considered as the index of the effectiveness of sand layer. The relative settlement decreases with increase of normalized value of thickness of upper sand layer i.e. $H/B$ for particular $q/\gamma_{sat}$ for all value of $e_{min}$. The relative settlement decreases at the same rate with the increase of thickness of upper sand layer $H/B$. For a particular value of $H/B$ increase of $S/S_0$ with $q/\gamma_{sat}$ is more significant for values of $q/\gamma_{sat}>2.5$. For $q/\gamma_{sat}<2.5$ $S/S_0$ at different $q/\gamma_{sat}$ are closer. For all value of $e_{min}$, $S/S_0$ decreases with increase of different $q/\gamma_{sat}$ for normalized value of thickness of upper sand layer $H/B$. The relative settlement decreases at a high rate with the increase of thickness of upper sand layer $H/B$ due to a certain value of normalized footing pressure which is 2.5. After this particular value of footing pressure, this rate of decrease of relative settlement is smaller. For a particular value of $H/B$ increase of $S/S_0$ with $q/\gamma_{sat}$ is more significant for $q/\gamma_{sat}>2.5$. For $q/\gamma_{sat}<2.5$ $S/S_0$ at different $q/\gamma_{sat}$ are closer.

The cement treated upper sand layer is more effective than untreated upper sand layer in reducing relative settlement $S/S_0$, for $q/\gamma_{sat}<2.5$ and for $q/\gamma_{sat}>2.5$, the effectiveness of untreated upper sand layer and cement treated upper sand layer is about similar in reducing relative settlement. For $H/B<0.5$ the cement treated upper sand layer is more effective than untreated upper sand layer in reducing relative settlement $S/S_0$, and for $H/B>0.5$ the effectiveness of untreated upper sand layer and cement treated upper sand layer is about similar in reducing relative settlement.

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