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# Design Charts for Strip Footing on Untreated and Cement Treated Sand Mat over Underlying Natural Soft Clay

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***Abstract*****—**Shallow foundations on unimproved soft natural soils can undergo a high consolidation and secondary settlement. For low and medium rise building projects on such soil condition, pile foundation may not be cost effective. In such cases an alternative to pile foundations may be shallow strip footings placed on a double layered improved soil system soil. The upper layer of this system is untreated or cement treated compacted sand and underlying layer is natural soft clay. This system will reduce the settlement to an allowable limit. The current research has been conducted with the settlement of a rigid plane-strain strip footing of 2.5 m width placed on the surface of a soil consisting of an untreated or cement treated sand layer overlying a bed of homogeneous soft clay. The settlement of the mentioned shallow foundation has been studied considering both cases with the thicknesses of the sand layer are 0.3 to 0.9 times the width of footing. The response of the clay layer is assumed as undrained for plastic loading stages and drained during consolidation stages. The response of the sand layer is drained during all loading stages. FEM analysis was done using PLAXIS 2D Version 8.0. A natural clay deposit of 15 m thickness and 18 m width has been modeled using Hardening Soil Model, Soft Soil Model, Soft Soil Creep Model, and upper improvement layer has been modeled using only Hardening Soil Model. The groundwater level is at the top level of the clay deposit that made the system fully saturated. Parametric study has been conducted to determine the effect of thickness, density, cementation of the sand mat and density, shear strength of the soft clay layer on the settlement of strip foundation under the uniformly distributed vertical load of varying value. A set of the chart has been established for designing shallow strip footing on the sand mat over thick, soft clay deposit through obtaining the particular thickness of sand mat for particular subsoil parameter to ensure no punching shear failure and no settlement beyond allowable level. Design guideline in the form of non-dimensional charts has been developed for footing pressure equivalent to medium-rise residential or commercial building foundation with strip footing on soft inorganic Normally Consolidated (NC) soil of Bangladesh having void ratio from 1.0 to 1.45.

***Keywords*****—**Design charts, ground improvement, PLAXIS 2D, primary and secondary settlement, sand Mat, soft clay.

## I. INTRODUCTION

THE bearing capacity of a vertically loaded footing placed on the surface of a homogeneous soil may be estimated shortly using the conventional bearing capacity theories adopting appropriate bearing capacity factors. This type of bearing capacity calculation is based on the assumption that the soil is rigid-perfectly plastic with the shear strength characterized by the cohesion and the friction angle. This approach is highly successful for homogeneous soils but generally it cannot be used where the soil properties are variable with depth. At first, design charts for ultimate bearing capacity for sands overlying clay were developed by [1]. Design guidelines for cement treated soil overlying clay were developed by [2]. When the foundation is placed on a layered soil system for which the thickness of the top improved layer is large compared to foundation width, then realistic estimation of the bearing capacity may be calculated using conventional bearing capacity theory based on the properties of layers of soil. But when the thickness of the top improved 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 of strip footings and deformation pattern or strain field of layered soil underlying the strip footings placed on this. The study considered both cases where the thickness of the sand layer is thin or thick comparable to the footing width and in all cases the ground surface and the interface between the two soil layers is horizontal. It has been assumed that the clay layer is undrained in plastic loading stages and drained in consolidation stages. The response of the sand layer is drained for all stages of loading. Generally the behavior of cemented sand is brittle, but in the current analysis, the fracture or cracks of the brittle cemented layer has not been considered.

## II. SELECTION OF SOIL PROPERTIES FOR THIS STUDY

Material properties used in this research have been taken from those obtained from previous literature on soft inorganic clay and river sand of Bangladesh [3]-[6]. For inorganic clay of Bangladesh, the value of Liquid Limit, $LL$ = 60% and Plasticity Index, $PI$ = 30% has been selected for this study [3], [4]. For NC clay: $E_u^{50} = \frac{15000c_u}{I_p\%}$ [7]. According to the PLAXIS manual for soft soil, $E_u$ may be converted into $E'$ by: $E' = \frac{2(1+v')}{3}E_u$ where $v' \leq 0.35$ [7]. For soft high plastic (CH) clay $c_u$ = 12 kPa, $E_u^{50}$ = 6000 kPa and $E'$ = 5000 kPa have been used [2], [3]. A value of 24° for Bangladeshi soft clay has been considered and used in this analysis [4]. Correlation between drained shear strength and PI of NC clay as $\phi'_{NC}$ (deg) = 43–10log $PI$ (deg) has been used [8]. As PLAXIS does not allow a zero value of drained cohesion and for that a unit

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value 1.0 kPa for these parameters have been used. An average value of dry density $\gamma_d$ of soft soil of Bangladesh may be considered as 1.5 g/cm$^3$ or 14.70 $\mathrm{kN/m^3}$ [4]. Using $\gamma_d$ = 14.70 $\mathrm{kN/m^3}$ and the relationship, $\gamma_{sat} = \gamma_d + \gamma_w \frac{e}{1+e}$ an average value of Saturated Unit Weight 20 $\mathrm{kN/m^3}$ was taken for the present study. The correlation for $C_c$ used in current study is $C_c$ = 0.0078 ($LL$– 14), which was developed for Plastic Silt and Clay of different area of Bangladesh [4]. A zero value of Swelling Index, $C_s$ is not allowed by PLAXIS and for this reason for NC clay a very small value of $C_s$ = 0.001 has been used in this analysis. The void ratio for inorganic clay of Bangladesh is as large as 1.463 [5]. LL is the mineralogical properties of a soil while the void ratio is a measure of density and may vary, keeping the LL fixed. Analysis has been carried out with fixed LL and four different value of void ratio and these are 1.00, 1.15, 1.30 and 1.45.

The characteristics of cemented clayey soil of Bangladesh were studied by some researchers, as has been found in literature such as [12], but no study has been found by the authors on cemented sand of Bangladesh. For this reason, literature related to properties of cement stabilization of sands in other countries has been reviewed. Parameters of cement treated sand required for the present analysis have been selected from [9].

## III. Subsoil System and Model Geometry for Current Analysis

During the modeling in PLAXIS 2D, a natural clay deposit of 15 m thickness and 18 m width has been used. A cement treated or untreated compacted sand layer of varying thickness is considered over the natural clay deposit. A 2.5 m wide concrete strip footing is installed at the center of top surface of the sand layer (Fig. 1). 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. A lot of analysis of this foundation system has been carried out using PLAXIS to get a better understanding of the primary and secondary settlement. The width of strip footing $B$ is kept constant for all the analysis done in this study. Analysis was done for different footing pressure $q$, vertical settlement $S$ and void ratio $e_{init}$ for different thickness of upper sand mat layer, $H_i$.

TABLE I
Material Set (Clay and Sand) Input Parameters for the Lower Clay Layer

| Parameter | Clay | | | Sand | | Unit |
|---|---|---|---|---|---|---|
| | Elastoplastic Stage | Consolidation Stage | Creep Stage | Untreated sand | Cement Treated | |
| Material Model | HS | SS | SSC | HS | HS | - |
| Drainage Condition | U | U | U | D | U | - |
| Poisson's Ratio, $v'$ | 0.2 | 0.15 | 0.15 | 0.2 | 0.2 | - |
| Saturated Unit Weight (below phreatic level), $\gamma_{sat}$ | 20 | 20 | 20 | 20 | 20 | kN/m$^3$ |
| Unsaturated Unit Weight (above phreatic level), $\gamma_{unsat}$ | 15 | 15 | 15 | 18 | 18 | kN/m$^3$ |
| Drained Cohesion, $c'_{ref}$ | 1 | 1 | 1 | 1 | 300 | kN/m$^2$ |
| Drained Friction Angle, $\phi'$ | 24 | 24 | 24 | 38 | 38 | degree |
| Dilatancy Angle, $\psi$ | 0 | 0 | 0 | 8 | 8 | degree |
| Initial Stress, $K_0$ = 1-sin$\phi'$(Jaky's formula) | 0.593 | 0.593 | 0.593 | 0.384 | 0.384 | - |
| Over Consolidation Ratio, $OCR$ | 1 | 1 | 1 | - | - | 1 |
| Interface Reduction Factor, $R_{inter}$ | 1 | 1 | 1 | 1 | 1 | - |
| Horizontal Permeability, $k_x$ | 1.0E-4 | 1.0E-4 | 1.0E-4 | 1 | 1.0E-5 | m/day |
| Vertical Permeability, $k_y$ | 1.0E-4 | 1.0E-4 | 1.0E-4 | 1 | 1.0E-5 | m/day |
| Triaxial Stiffness, $E_{50}^{ref}$ | 5000 | - | - | 5.0E+4 | 6.0E+5 | kN/m$^2$ |
| Oedometer Stiffness, $E_{oed}^{ref}$ | 4750 | - | - | 4.75E+4 | 5.7E+5 | kN/m$^2$ |
| Unloading/Reloading Stiffness, $E_{ur}^{ref}$ | 15000 | - | - | 1.5E+5 | 1.8E+6 | kN/m$^2$ |
| Power, $m$ (Required for HS Model) | 1.00 | - | - | 0.5 | 0.5 | - |
| Compression Index, $C_c$ | - | 0.36 | 0.36 | - | - | - |
| Swelling Index, $C_s$ | - | 0.001 | 0.001 | - | - | - |
| Creep Index, $C_\alpha$ | - | - | 0.018 | - | - | - |
| Natural Void Ratio, $e_{init}$ | 1.00, 1.15, 1.30 and 1.45 | | | 0.5 | 0.5 | - |

The bottom layer is a homogenous soft clay layer with effective shear strength parameters $c'$ and $\phi'$. $\gamma_{sat}$ is saturated unit weight of the bottom clay layer. The size of the finite element model is 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 soils were modeled with three material models-Hardening Soil (HS) Model, Soft Soil (SS) Model and Soft Soil Creep (SSC) Model according to previous literature [8], [10]. The HS model is used to simulate the untreated and cement treated sand layer and the SS and SSC model is used to simulate clay layer. The input parameters for materials used in different models are represented in Tables I and II.

An elongated footing foundation which supports load bearing walls or a single row of columns are generally referred to as strip footings, which have been used to carry out current two-dimensional finite element analyses. Loads and boundary conditions are independent of the largest dimension. As a result, the strains in the direction of z-axis are considered to be zero. A 15-node triangular element having 12 stress points is used in current analysis. And interface elements are automatically taken to be compatible with the selected type of element for adjacent soil. Strip footing has been modelled through the plate element composed of beam elements having three degrees of freedom per node having five nodes with 15 noded soil elements.

TABLE II
MATERIAL PARAMETERS FOR THE CONCRETE STRIP FOOTING

| Input Parameter | Parameter Value | Unit |
|---|---|---|
| Material Type | Plate | - |
| Material Model | Elastic | - |
| Drainage Condition | Undrained | - |
| Normal Stiffness, *EA* | 4.5E+07 | kN/m |
| Flexural Rigidity, *EI* | 1.35E+06 | $kNm^2/m$ |
| Equivalent Thickness, *d* | 0.60 | m |
| Poisson's Ratio, $v'$ | 0 | - |
| Weight, *w* | 0 | kN/m/m |

Interface elements are used to simulate the interaction between two materials. The strength of the interface has been changed using $R_{inter}$ = 0.7-0.8 for cohesive soil and 0.9 for frictional soil. The standard value of the virtual thickness factor is 0.1. The standard fixities option has been used as boundary condition which is commonly used in many geotechnical problems, and is quick and comfortable. This boundary type restricts both horizontal and vertical displacements to zero at the bottom boundary and horizontal displacements to zero at the side boundaries. The width of the model is chosen so that the boundary conditions did not introduce constrain, this was controlled by observing a normal shear stress distribution at the boundaries. The clusters were arranged so that the provision of an artificial sand layer could be simulated, using a staged calculation. Distributed load has been applied in the *y*-direction only. 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 U-Undrained or D-Drained.

At first the mesh is generated by using a coarse mesh. Then, the mesh at the surrounding location of the footing plate has been changed to a fine mesh using the refinement option of PLAXIS for better accuracy of results (Fig. 2). Defining the initial conditions has been done to assign the history of the soil, $K_0$ and *OCR*. In the initial conditions, the hydrostatic pore water pressures are based on a general phreatic level (groundwater table). For the consolidation analysis, closed consolidation boundary has been chosen at the left and right side of the geometry (two vertical boundaries). The bottom horizontal boundary is automatically closed consolidation boundary and the top of the geometry is kept open for consolidation. The plastic and consolidation calculation has been done with 'Updated mesh analysis', 'Updated water pressure analysis' and 'Ignore undrained behavior'. The period of secondary compression is 10-30 years. 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. The three subsequent phases are as follows: Phase 1: Strip footing plate and load is activated in this phase. Elastoplastic deformation of the system under assigned load is calculated in this phase. Phase 2: Deformation of the system due to consolidation under the load applied at 'Phase 1' is calculated. The consolidation settlement is occurred in this phase through dissipation of pore water pressure up to a very small value which is 1.0 $kN/m^2$. Phase 3: No additional load is activated in this phase. Full dissipation of pore water pressure occurs. Then, the inter particle re-arrangement or creep occurs without application of any additional load. Creep deformation of the problem geometry under load applied at 'Phase 2' is calculated in this phase.

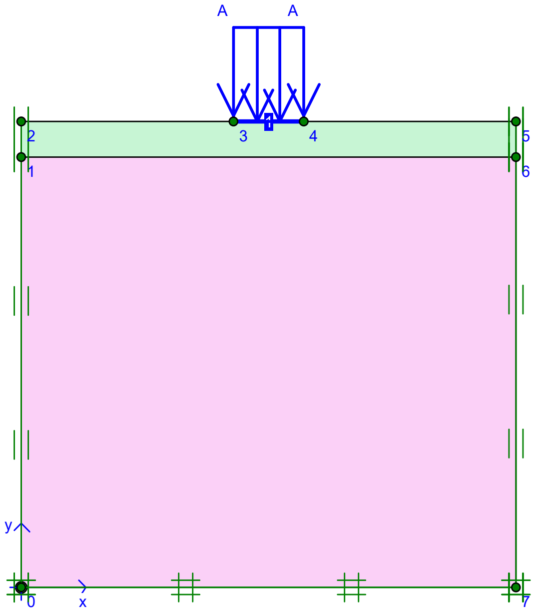


Fig. 1 PLAXIS Model Geometry

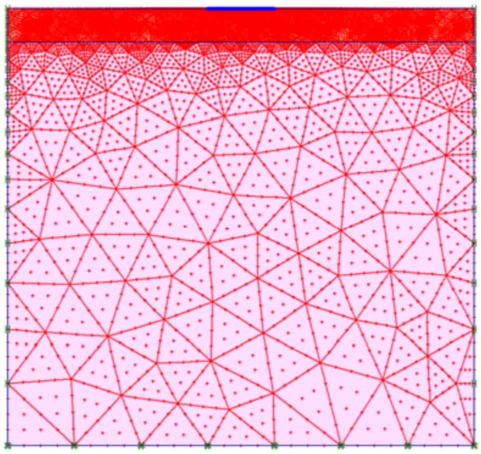

Fig. 2 Finite Element Mesh for the Geometry Model

The load that causes bearing capacity failure or soil body collapse of surface footing used in the current analysis is less than that for footing embedded into the ground. The elasto-plastic and consolidation settlement obtained from PLAXIS analyses are 61-87% and 64-66% respectively compared to calculated values of these from classical theory.

## IV. Analysis of Results

The dimensionless forms for a wide range of values are used to generalize their effect. Here, $H_i/B$ is the non-dimensional layer thickness, $q/\gamma_{sat}B$ is the non-dimensional loads on strip footings. The values of $H_i$ (m) used in the analysis are 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25. The values of relative depth $H_i/B$ 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, 5, 2.5, 3, 3.5 and 4. The values of $q$ (kN/m$^2$) = 50, 75, 100, 125, 150, 175, 200 has been used which are similar to foundation pressure of three to eight storied residential or commercial buildings. Settlement (downward vertical displacement) of footing center (midpoint of footing plate) obtained from PLAXIS analyses is denoted as $S$ when $H_i$ = 0.75 m-2.0 m. In this way sand layer thickness, $H_i$ = 0.75 m or more has been studied for improvement purpose of the ground.

## V. Design Guideline

This guideline is developed for strip footing on the soft inorganic NC clay of Bangladesh having void ratio 1.0 to 1.45.

The research work was limited on a single $E'$ and $\phi'$ value of the soft clay layer and also a single $\phi'$ value of the sand mat. These design charts may be used to obtain total settlement for particular values of footing pressure ($q$), sand mat thickness ($H_i$), footing width ($B$) and initial void ratio ($e_{init}$).

### *A. Design Charts for Untreated Sand Mat*

Design charts in the form of $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ may be used to obtain total settlement, $S$ for $q$, $H_i$, $B$ and $e_{init}$ using different charts for different $H_i/B$. From $S/H_i$ vs. $q/\gamma_{sat}B$ graphs for different $H_i/B$ for different value of natural void ratio are plotted and presented in Figs. 3 (a)-(d). These design charts may be used to obtain total settlement, $S$ for particular values of footing pressure ($q$), sand mat thickness ($H_i$) and footing width ($B$) using different chart for different initial void ratio ($e_{init}$).

### *B. Design Charts for Cement Treated Sand Mat*

Design charts in form of $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ may be used to obtain total settlement, $S$ for $q$, $H_i$, $B$ and $e_{init}$ using different chart for different $H_i/B$. From $S/H_i$ vs. $q/\gamma_{sat}B$ graphs for different $H_i/B$ for different values of natural void ratio are plotted and presented in Figs. 4 (a)-(d). These design charts may be used to obtain total settlement, $S$ for particular values of footing pressure ($q$), sand mat thickness ($H_i$) and footing width ($B$) using different chart for different initial void ratio ($e_{init}$).

### *C. Design for Permissible Settlement*

The permissible settlement as per BNBC 2017 [11] is 50 mm. Design thickness of an untreated sand mat for permissible settlement of 50 mm may be obtained using the charts represented in Figs. 3 (a)-(d). Similarly, design thickness of cement treated sand mat for permissible settlement of 50 mm may be obtained using the charts represented in Figs. 4 (a)-(d).

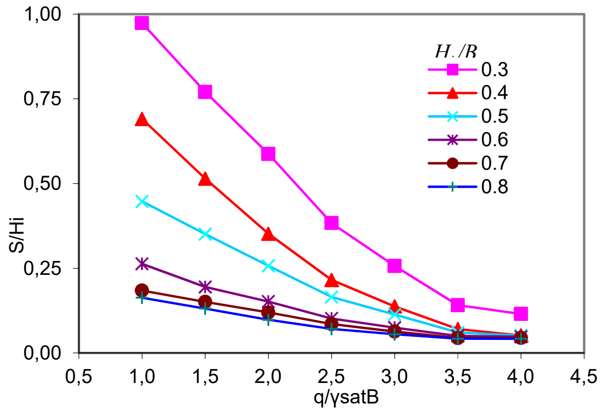


Fig. 3 (a) $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.0

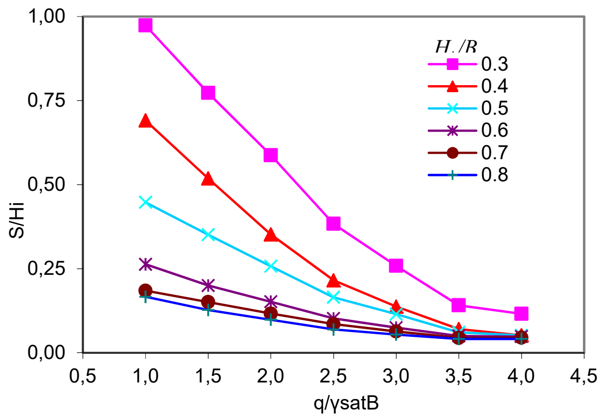


Fig. 3 (b) $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.15

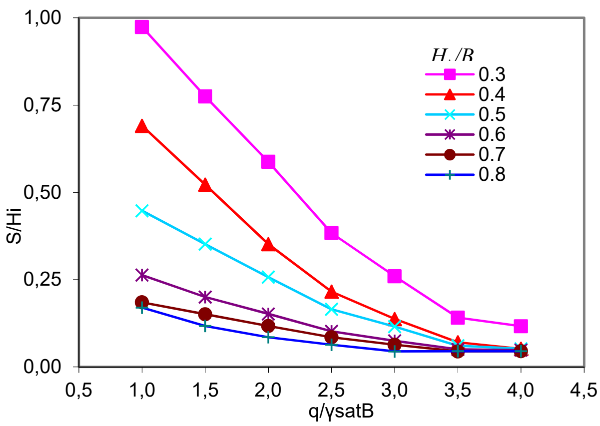


Fig. 3 (c) $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.3

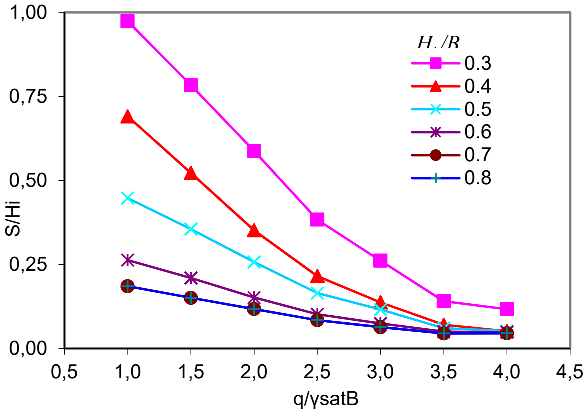


Fig. 3 (d) $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.45

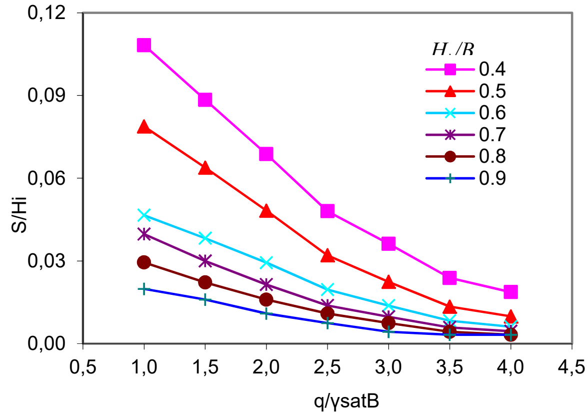


Fig. 4 (c) $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.30

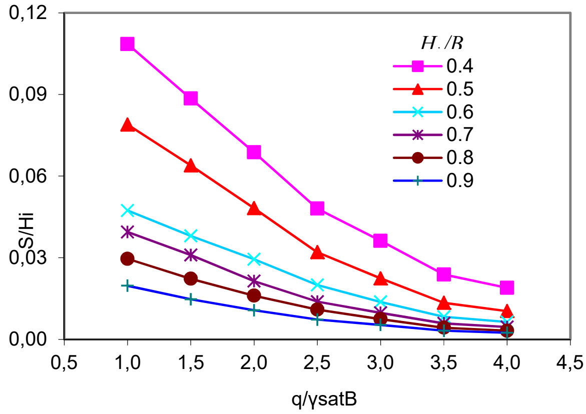


Fig. 4 (a) $S/H_i$ with $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.00

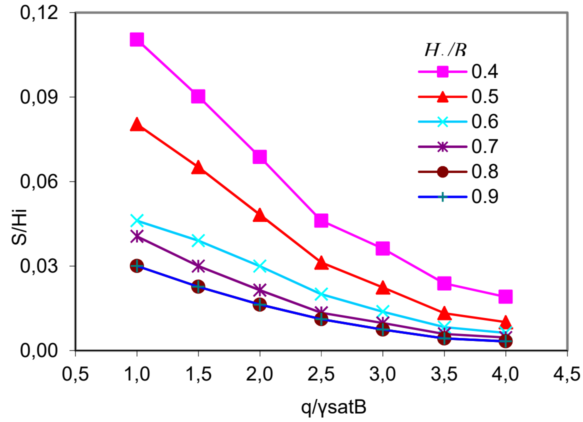


Fig. 4 (d) $S/H_i$ vs $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.45

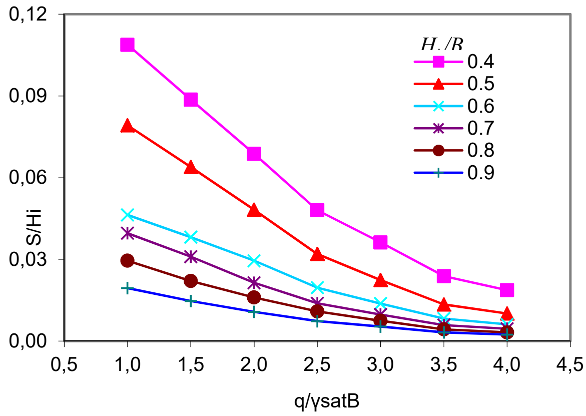


Fig. 4 (b) $S/H_i$ with $q/\gamma_{sat}B$ for different $H_i/B$ at $e_{init}$ = 1.15

## VI. Conclusion

A better control of elasto-plastic, consolidation and creep settlements of a strip footing on sand mat under different footing pressure equivalent to low or moderately loaded low to medium rise residential or commercial building loads has been developed.

Guidelines have been established for designing shallowstrip footing with sand mat on thick soft NC clay deposits of Bangladesh having a void ratio 1.0 to 1.45 to determine the thickness of the sand mat for different material characteristics to avoid punching shear failure and to limit the settlement to an allowable level.

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