Guideline for Designing Strip Footing on Sand Mat underlain by Thick Soft Clay

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Abstract—Shallow foundations on soft soils deposit without any ground improvement can undergo a high reduction in volume after consolidation and secondary settlement. For low and medium rise building projects on such soil condition, a deep foundation may not be economically feasible. In such cases an alternative to deep foundations may be shallow strip footings placed on a double layer foundation system in which the upper layer is untreated or cement treated compacted sand to reduce the settlement of underlying natural soft clay to a permissible level. This research work deals with the specific case of the settlement of a rigid plane-strain strip footing of 2.5m width placed on the surface of a soil consisting of an untreated or cement treated sand layer overlying a thick, homogeneous bed of soft clay. The settlement of mentioned shallow foundation has been studied considered both the cases where the thickness of the sand layer is thin or thick compared to the footing width. It is assumed that the response of the clay layer is undrained for plastic loading stages and drained in consolidation stages and the response of the sand layer is drained in all loading stages. FEM analysis was done using PLAXIS 2D Version 8.0. A natural clay deposit of 15m thickness and 18m 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. Ground water level is at top level of clay deposit that made the system fully saturated.

Parametric study has been conducted to determine the effect of thickness, density, cementation of sand mat and density, shear strength of the soft clay layer on the settlement of strip foundation under uniformly distributed vertical load of varying value. A guideline has been established for designing shallow strip footing on sand mat over thick soft clay deposit through determining the thickness of sand mat for different material characteristics to avoid punching shear failure and to limit the settlement to an allowable level. A design guideline in form of design chart and design equation has been developed for footing pressure equivalent to medium rise residential or commercial building foundation with strip footing on soft inorganic NC soil of Bangladesh having void ratio from 1.0 to 1.45. For a specific value of settlement such as permissible settlement of 50mm as per BNBC 2017, the design thickness of sand mat may be obtained using the proposed charts and equations.

Index Terms—Design guideline, ground improvement, primary and secondary settlement, PLAXIS 2D, soft clay.

1 INTRODUCTION

THE bearing capacity of a vertically loaded footing placed on the surface of a homogeneous soil may be estimated shortly using conventional Terzaghi's or Meyerhof 's bearing capacity theory in which appropriate values of the bearing capacity factors are adopted. This type of calculation is based on the implicit assumption that the soil is rigid-perfectly plastic with the strength characterized by cohesion and an angle of friction. Whilst this approach is highly successful for homogeneous soils, it cannot, in general, be used for cases where the soil properties vary with depth. At first design charts for ultimate bearing capacity for sands overlying clay was developed by Hanna and Meyerhof [1]. Design guideline for cement treated soil overlying clay was developed by Thomé et. al. [2]. If a foundation is placed on the surface of a layered soil for which the thickness of the top layer is large compared with the width of the foundation, then realistic estimates of the bearing capacity may be obtained using conventional bearing capacity theory based on the properties of the two soil layer. If the thickness of the top layer is comparable to the foundation width, however, 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 the 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 is assumed that the response of the clay layer is undrained for plastic loading stages and drained in consolidation stages and the response of the sand layer is drained in all loading stages. Brittle behavior of cemented sand and fracture or cracks is not considered in current analysis.

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2 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 Normally consolidated clay: $E_u^{50} = \frac{15000c_u}{I_p\%}$ [7]. According to PLAXIS manual for soft soil, E_u may be converted into E' by: $E' = \frac{2(1+v')}{3}E_u$ where ν′ ≤ 0.35 [7]. For soft high plastic (CH) clay c_u = 12kPa, 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 plasticity index of NC clay as ϕ'_{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 value 1.0 kPa for these parameters have been used. An average value of dry density γ_d of soft soil of Bangladesh may be considered as 1.5 g/cm³ or 14.70 kN/m³ [4]. Using γ_d =14.70 kN/m³ and the relationship, $\gamma_{sat} = \gamma_d + \gamma_w \frac{e}{1+e}$ an average value of Saturated Unit Weight *is* 20 kN/m³ was taken for the present study. Correlation for C_c of Plastic Silt and Clay of different area of Bangladesh which is, C_c = 0.0078(LL– 14) [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]. 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. Analysis has been carried out with fixed Liquid limit 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 was studied by some researcher as has been found in literature but no study could be found on Cemented sand of Bangladesh. For this reason literature related to properties of cement stabilization of sands in other countries have been reviewed and parameters of cement treated sand required for the present analysis have been selected from those found from literature [9].

3 SUBSOIL SYSTEM AND MODEL GEOMETRY FOR CURRENT ANALYSIS

During the modeling in PLAXIS 2D, a natural clay deposit of 15m thickness and 18m width has been used. A cement treated or untreated compacted 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 (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. 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 1
MATERIAL SET INPUT PARAMETERS FOR THE LOWER CLAY LAYER

Parameter	Material Set					Unit
	Clay			Sand		
	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), γ_{sat}	20	20	20	20	20	kN/m³
Unsaturated Unit Weight (above phreatic level), γ_{unsat}	15	15	15	18	18	kN/m³
Drained Cohesion, c'_{ref}	1	1	1	1	300	kN/m²
Drained Friction Angle, ϕ'	24	24	24	38	38	degree
Dilatancy Angle, ψ	0	0	0	8	8	degree
Initial Stress, K_0=1-sin ϕ' (Jaky's formula)	0.593	0.593	0.593	0.384	0.384	-
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

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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_α	-	-	0.018	-	-	-
Natural Void Ratio, e_{init}	1.00 1.15 1.30 1.45	1.00 1.15 1.30 1.45	1.00 1.15 1.30 1.45	0.5	0.5	-
U -Undrained and D -Drained						

The bottom layer is a homogenous soft clay layer with effective shear strength parameters c' and ϕ'. γ_{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]. 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 Table I & Table II.

An elongated footing foundation which support load bearing walls or a single row of columns are generally referred to as strip footings, which has 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. 15-node triangular element having 12 stress points is used in current analysis. and interfaces elements is 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 2
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 this 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 artificial sand layer could be simulated, using a staged calculation. Distributed load has been applied in *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 drained or undrained.

At first the mesh is generated by using a coarse mesh. Then 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 (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 boundary). 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'. 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. Three subsequent phases are as follows:

Phase 1: 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: 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: 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. The load that causes bearing capacity failure or soil body collapse of surface footing used in current analysis is less than that for footing embedded into ground. Elasto-plastic and Consolidation settlement obtained from PLAXIS analysis is 61-87% and 64-66% of calculated values of these from classical theory successively.

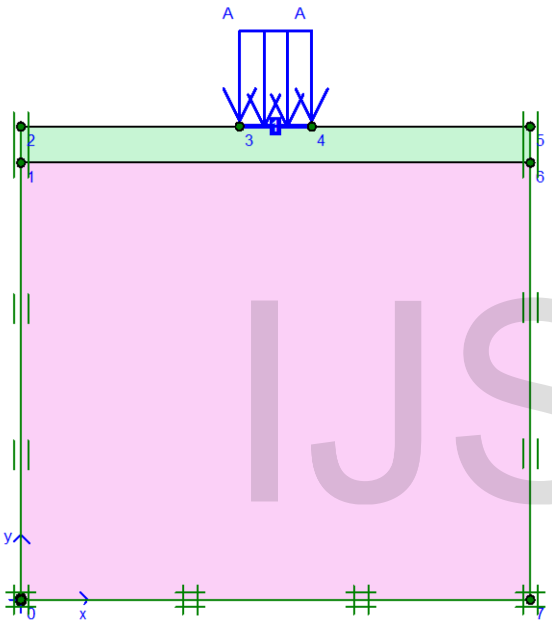

Fig. 1 Plaxis Model Geometry.

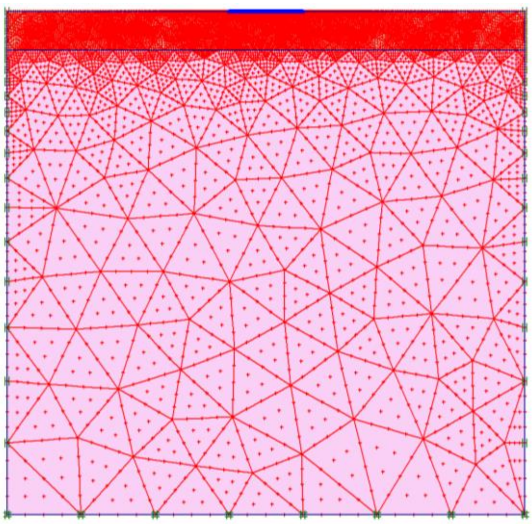

Fig. 2 Finite Element Mesh For The Geometry Model.

4 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. In the analysis the values of H_i (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 are used which are similar to foundation pressure of three to eight storied residential or commercial buildings. 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. Settlement (downward vertical displacement) of footing centre (midpoint of footing plate) obtained from PLAXIS analyses is denoted as S when H_i (m)=0.75m-2.0m. The bearing capacity failure occurred before completion of application of total load if the system analyzed without any sand mat. 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. Settlement at midpoint of footing plate is S_0 when H_i=0.25m without any sand mat. Sand layer thickness, H_i=0.75m or more has been studied for improvement purpose of the ground.

5 Design Guideline

This guideline is developed for strip footing on soft inorganic NC soil of Bangladesh having void ratio 1.0 to 1.45. The research work was limited on a single E' and ϕ' value of soft clay layer and also a single ϕ' value of 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}).

5.1 Design Guideline for Untreated Sand Mat

Design charts in form of S/H_i vs $q/\gamma_{sat}B$ for different e_{init} 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 e_{init} are almost same. To avoid the very little effect of void ratio S/H_i for average void ratio has been plotted and is presented in Fig. 3.1. Logarithmic form of that chart is presented in Fig. 3.2. 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}).

5.2 Design Guideline for Cement Treated Sand Mat

Design charts in form of S/H_i vs $q/\gamma_{sat}B$ for different e_{init} are presented in Fig. 4.1. Logarithmic form of that chart is presented in Fig. 4.2. These charts may be used to obtain total settlement, S for particular values of footing pressure (q), Sand mat thickness (H_i), footing width (B) and initial void ratio (e_{init}) using different chart for different H_i/B. S/H_i vs $q/\gamma_{sat}B$ graphs for different e_{init} are almost same. To avoid the very little effect of void ratio S/H_i for average void ratio has been plotted.

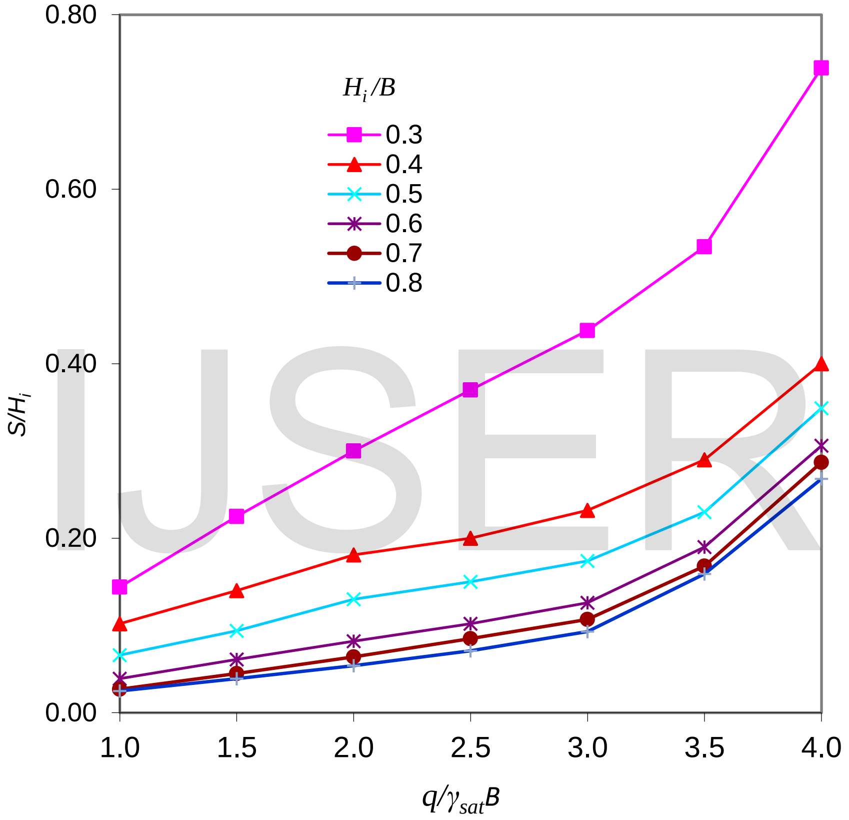

Fig. 3.1 Variation of S/S_0 with $q/\gamma_{sat}B$ for different H_i/B

5.3 Equation for Design

Combined logarithmic design chart for untreated sand is as upper layer presented in Fig. 3.2. The curves in that chart for different $\frac{S}{H_i}$ may be converted to exponential equation. The common equation for untreated sand is as upper layer obtained and given below as Equation 1.1. This equation may be written another form specifying the value of settlement equal to a permissible value and this form of that equation is also given below as Equation 1.3. For untreated sand as upper layer settlement of strip footing may be calculated for particular value of H_i, q, B and γ_{sat} using design chart or equations.

$$\frac{S}{H_i} = a\left(10^{b\frac{q}{\gamma_{sat}B}}\right) \quad (1.1)$$

where,

H_i/B	0.3	0.4	0.5	0.6	0.7	0.8
a	0.010	0.072	0.042	0.022	0.014	0.012
b	0.217	0.180	0.219	0.275	0.317	0.324

For a specific value of settlement the design thickness of sand mat may be obtained using Equation 1.2.

$$H_i = \frac{1}{a}\left(10^{-b\frac{q}{\gamma_{sat}B}}\right) S \quad (1.2)$$

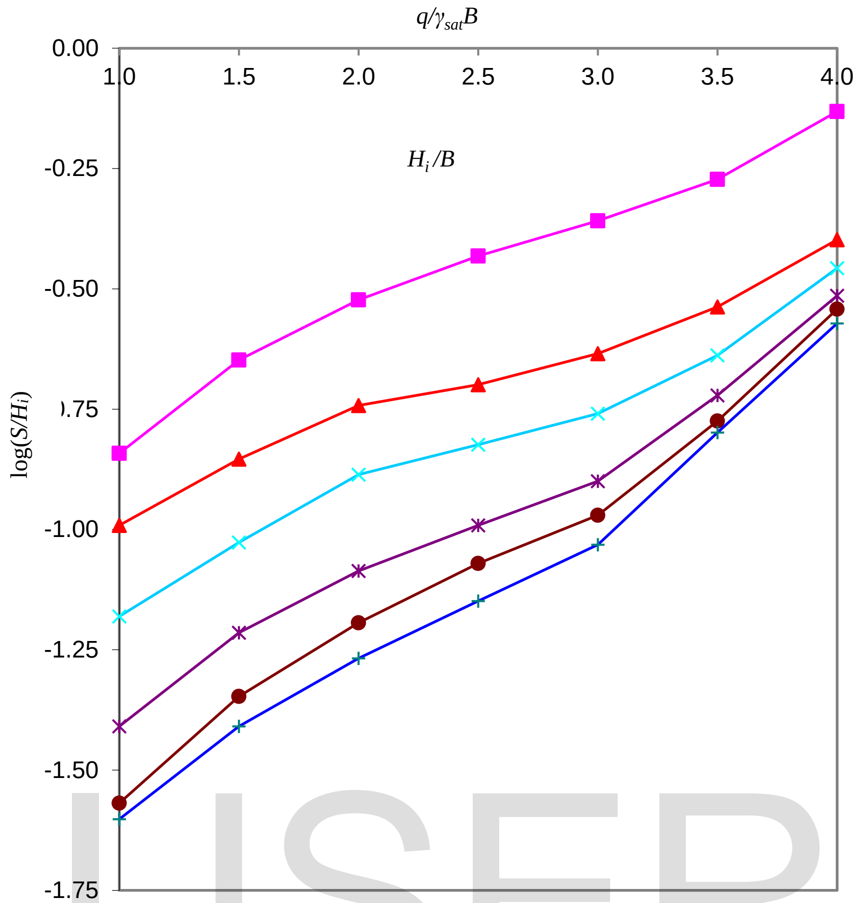

Fig. 3.2 Variation of S/S_0 with $q/\gamma_{sat}B$ for different H_i/B

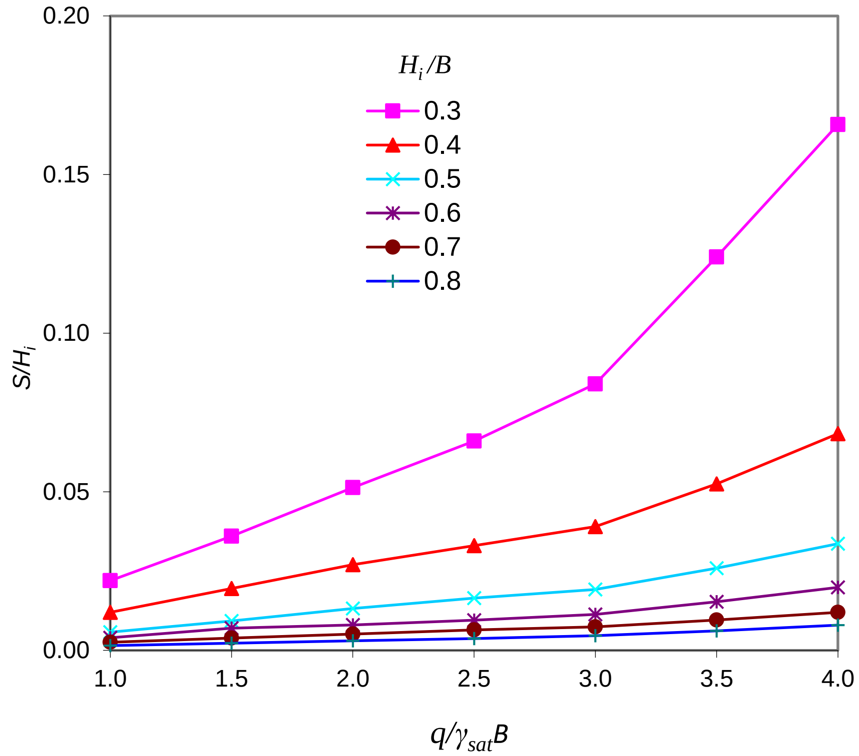

Fig. 4.1 Variation of S/S_0 with $q/\gamma_{sat}B$ for different H_i/B at e_{init} =1.00

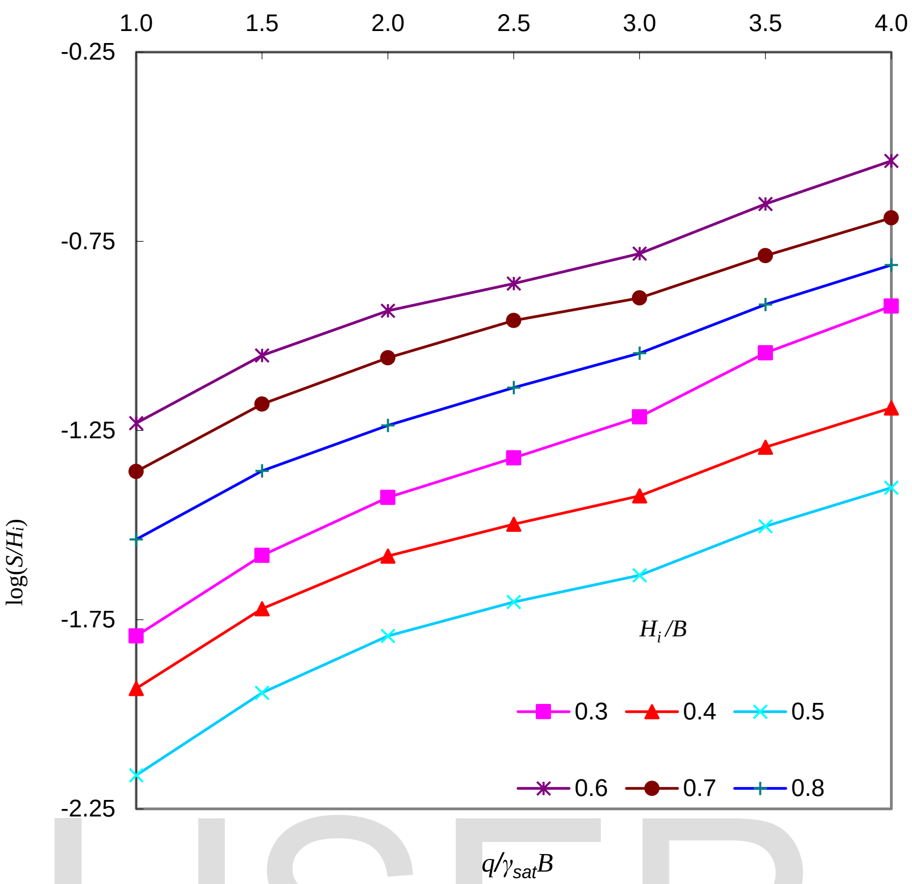

Fig. 4.2 Variation of log(S/H_i) with $q/\gamma_{sat}B$ for different H_i/B at e_{init}=1.00

The permissible settlement as per BNBC 2015 is 50mm [11]. The equation has been converted to equations 1.3 for unique settlement. Design thickness of sand mat for possible settlement of 50mm may be obtained using this equation.

$$H_i(mm)= \frac{50}{a}\left(10^{-b\frac{q}{\gamma_{sat}B}}\right) \qquad (1.3)$$

Combined logarithmic design chart for Cement Treated sand is as upper layer presented in Fig. 4.2. The curves in that chart for different $\frac{S}{H_i}$ may be converted to exponential equation. The common equation for Cement Treated sand is as upper layer obtained and given below as Equation 2.1. This equation may be written another form specifying the value of settlement equal to a permissible value and this form of that equation is also given below as Equation 2.3.

For Cement Treated sand as upper layer settlement of strip footing may be calculated for particular value of H_i, q, B and γ_{sat} using design chart or equations.

$$\frac{S}{H_i} = a\left(10^{b\frac{q}{\gamma_{sat}B}}\right) \qquad (2.1)$$

where,

H_i/B	0.3	0.4	0.5	0.6	0.7	0.8
a	0.039	0.030	0.019	0.010	0.005	0.012
b	0.216	0.211	0.231	0.278	0.231	0.237

For a specific value of settlement the design thickness of sand mat may be obtained using Equation 2.2.

$$H_i = \frac{1}{a}\left(10^{-b\frac{q}{\gamma_{sat}B}}\right)S \qquad (2.2)$$

The equation has been converted to equations 2.3 for unique settlement. Design thickness of sand mat for possible settlement of 50mm may be obtained using this equations.

$$H_i(mm)= \frac{50}{a}\left(10^{-b\frac{q}{\gamma_{sat}B}}\right) \qquad (2.3)$$

6 Conclusion

A better control of elasto-plastic, consolidation & 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.

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Guidelines have been established for designing shallow strip footing with sand mat on thick soft NC clay deposit of Bangladesh having void ratio 1.0 to 1.45 to determine the thickness of sand mat for different material characteristics to avoid punching shear failure and to limit the settlement to an allowable level. Design charts and equations are developed for strip footing on soft inorganic NC soil. For a specific value of settlement the design thickness of sand mat may be obtained using different Equations. Design thickness of sand mat for possible settlement of 50mm may be obtained using separate equations. The approach should be considered as replacement of weak top soil or for low fills needed to reach a specified ground level to carry load of footings for low or medium rise buildings constructed on this artificial layer.

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