Linear Axi-symmetric Finite Element Analysis of Concrete Piles in Nonhomogeneous Clay Soil

by

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Introduction

Load transfer mechanism of a axially loaded slender floating pile in clay deposits is mainly governed by the behaviour of interface between pile shaft and the surrounding soil. Load on the pile is primarily resisted by shear stresses developed on the interface and a small amount by bearing at the pile tip. The system behaves linearly upto a certain stage of loading but with further increase in load, interface develops a zone of local shear failure and as such the system deviates from linearity. This zone of local shear failure extends with increase in load and at an ultimate load, local shear failure covers whole interface and thus causing total collapse of the system.

A perusal of literatre indicates that very simple to highly complex theoretical approaches have been so far suggested for finding out the load transfer mechanism in a soil mass surrounding the pile. But most of the classical approach overlook many of the factors that play a vital role in the phenomenon.

In this, paper, a simplified finite element analysis has been evolved for the axially loaded pile clay system in the elastic region with a suitably developed general purpose computer programme capable to handle non-homogeneous as well as homogeneous nature of clay and also different pile geometry and different pile penetration.

Description of Problem

Concrete piles in cohesive soil strata represent commonly encountered feature of foundation engineering. In majority of the cases, it may happen that the soil mass would appear to be homogenous, in the sense that the samples taken at various depth would classify the soil into some soil type, yet, on testing, the soil samples would reveal that their strength, and hence, "*E*" i.e., modulus of Elasticity varies with depth. This makes the soil mass non-homogeneous with respect to "*E*".

The nature of variation in "*E*" would be function of the history of soil formulation and in general "*E*" would vary with depth, at random. Often,

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however, we encounter cohesive soil strata, wherein we could assume linear variation of "E" with depth, such as shown in Figure 1. Hundred cases of concrete piles in such soils were analysed, with the details of the cases as given below.

(*a*) All the piles had five slenderness ratios (L/d) namely 10, 25, 50, 100, 200.

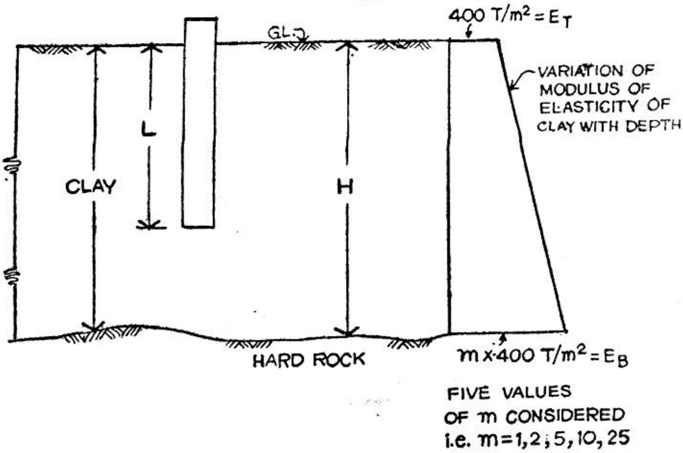

FIGURE 1 Variation of modulus of elasticity of clay

(*b*) The degree of penetration, (L/H) was assigned four values in turn viz; $L/H = 0.25, 0.5, 0.75$ and 1.0.

(*c*) Denoting the modulus of elasticity of the soil mass at the top of the soil stratum by "E_T" and that at the base of the soil stratum by "E_B", the degree of non-homogenity of the soil mass was defined by a ratio $m = E_B/E_T$. In the investigation, for each value of L/H and L/d, m was assigned the values of 1, 2, 5, 10 and 25 in turn. It should be noted that $m = 1$, represents case of homogeneous soil stratum, and it was included in the analysis to serve as a reference for the comparative study between the piles in homogenous and non-homogeneous soils.

Finite Element Idealization and Solution Details

The axi-symmetric finite elemeni idealization employed in the analysis for various cases had certain common features, and some variable features, dependent on the degree of penetration L/H. Complete idealization for $L/H = 0.5$ is shown in Figure 2. It may be noted that the common features keeping in view the details presented in Figure 2, are as given below.

(*a*) In all the cases the lateral extent of soil mass upto $R = 20.5\ d$ was considered.

(*b*) Ring elements with rectangular cross-section were employed, with the mesh size graded as function of "d" in "R" direction and twenty equal layers with each layer having a depth of 1 metre in "Z" direction.

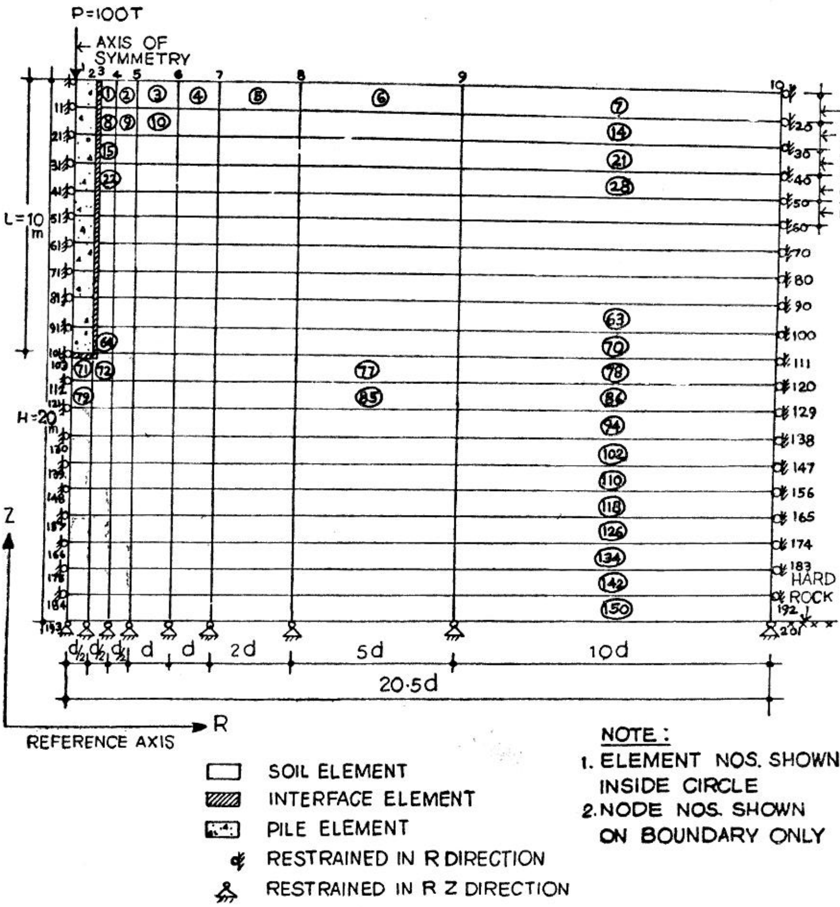

FIGURE 2 Finite element idealization for $L/H = 0.50$

In the numerical analysis, "*H*" was assigned a value of 20 m and axial load a value of 100 Ton. Key features of the schemes of idealization employed in the analysis for $L/d = 10$ were as presented in Table 1.

TBALE 1

Analysis for $L/d = 10$

L/h	L (m)	$d = L/10$ (m)	$r = 20.5d$ (m)	No. of soil elements	No. of pile elements	No. of inter-face ele-ment	Total No. of ele-ments	Total No. of nodes
0.25	5	0.5	10.25	155	5	6	166	196
0.50	10	1.0	20.50	150	10	11	171	201
0.75	15	1,5	30.75	145	15	16	176	206
1.00	20	2.0	41.00	140	20	21	181	211

The stiffness of pile elements and interface elements were calculated by assigning following values to the deformation modulii.

(*a*) For pile element $E_p = 2 \times 10^6$ ton/m² (Modulus of Elasticity)

$\mu_p = 0.15$ (Poisson's ratio)

(*b*) For interface elements

$K_s = K_n = 10^9$ T/m²/m, where

K_s = rigidity modulus against shear force,

K_n = rigidity modulus against normal force,

For calculating stiffness of the soil elements, "E_T" was assigned the value of 400 T/m² and μ_s (Poisson's ratio) the value of 0.45 ($\mu_s/\mu_p = 3$). Following the linear variation of "*E*" (Figure 1) with depth, the value of "*E*" at the Gaussian points of the soil elements were calculated to generate the rigidity matrix ($[c]_p$ and $[c]_s$) at each of the Gaussian points.

Following boundary conditions were employed :

(*a*) Nodes over the base of the soil stratum were restrained both "*R*" and "*Z*" directions.

(*b*) Nodes over the axis of symmetry were restrained in "*R*" direction only.

(*c*) It was assumed that the nodes over extreme vertical face of the idealized sections at $R = 20.5\,d$, do not suffer radial displacements. Hence those nodes were treated as if restrained in "*R*" direction.

Vertically downward load of 100 Ton was applied at the centre of the pile, in each case. The average of the settlement (*s*) suffered by the pile centre and the pile periphary was calculated to estimate the settlement of pile top. Stresses at the Gaussian points (Figure 3) of the interface elements were calculated for defining load transfer characteristics between the piles and the soil strata.

It was observed that behaviour of the pile-soil systems with L/H, were radically different from the systems with $L/H < 1$. Consequently results pertaining to these two catagories are discussed separately.

Results and Discusison

Interface Shear Stresses

Let "*T*" be the shear stress at a depte "*Z*" (depth of Gaussian point) over the interface between the pile shaft and soil mass. We shall represent "*T*" through a non-dimensional parameter "I_s" as defined below.

$$I_s = \frac{T.\pi.d.L}{P}$$

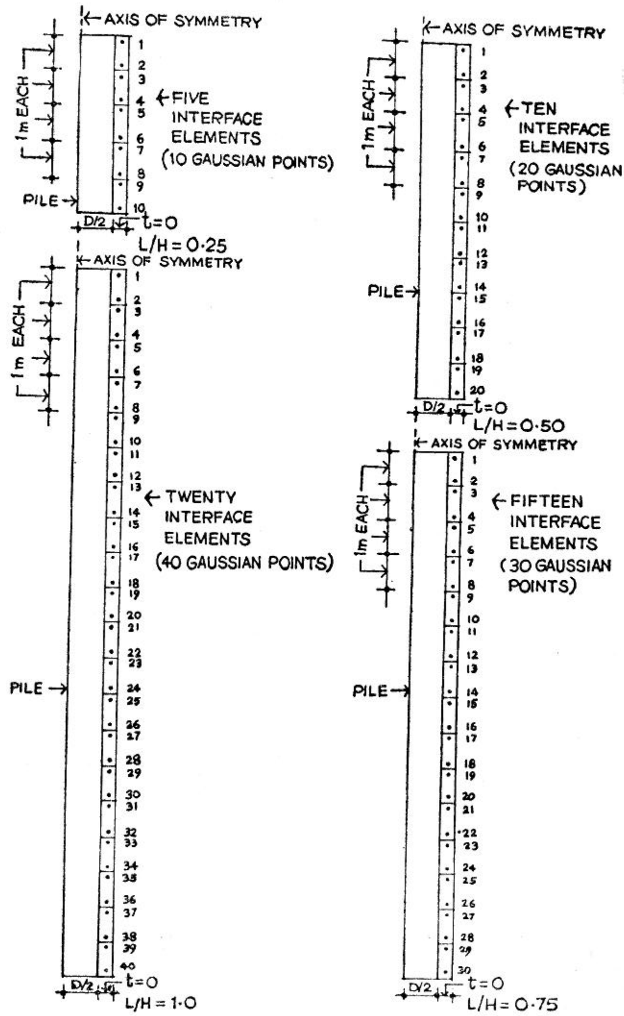

FIGURE 3 Vertical interface elements with Gaussian points

Influence of "m"

To appreciate the influence of "m" (ie., degree of nonhomogenity), it is referred to the plots presented in Figure 4 to Figure 8. It may be noted that for $L/H = 0.25$, 0.5 and 0.75 the figures show variation of I_s with depth (Z/L). For each L/H, curves are drawn for different "m" values. From the figuree it is observed that,

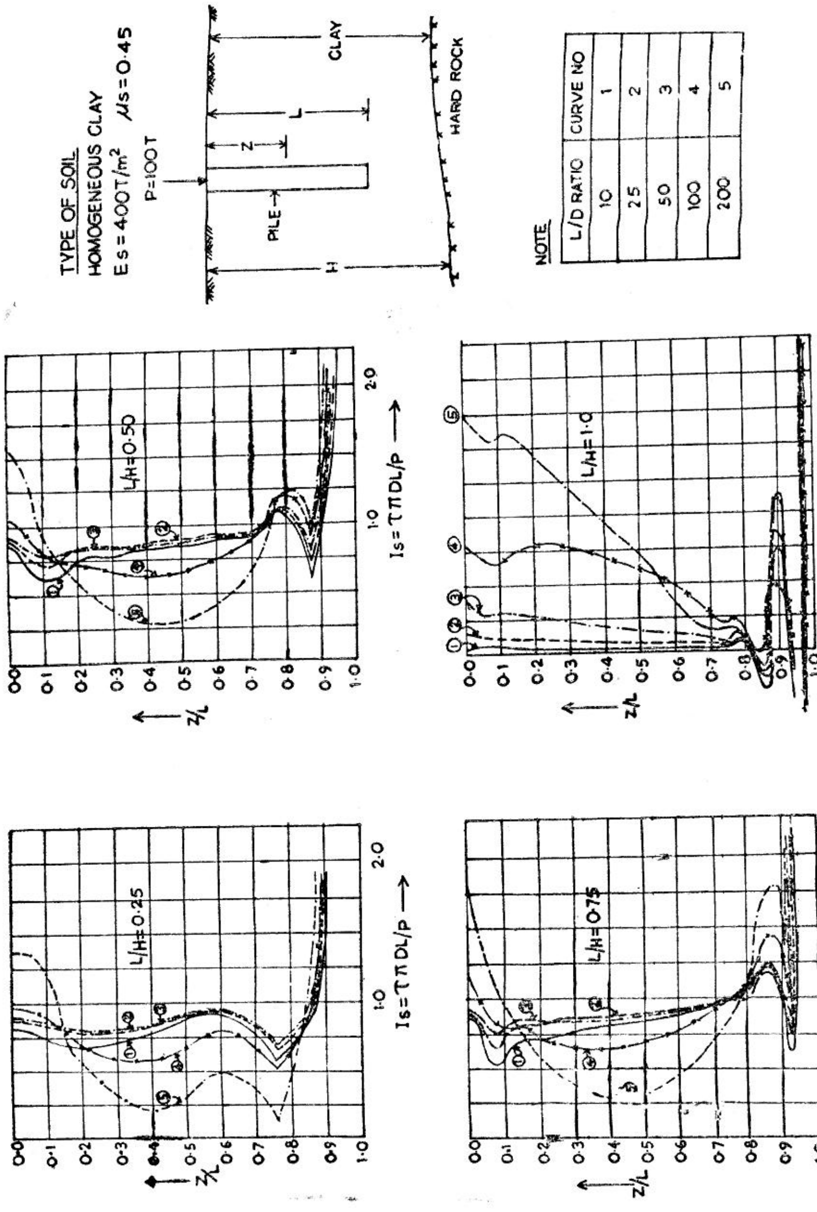

FIGURE 4 Variation of nondimensional influence factor for shear stress (I_s)

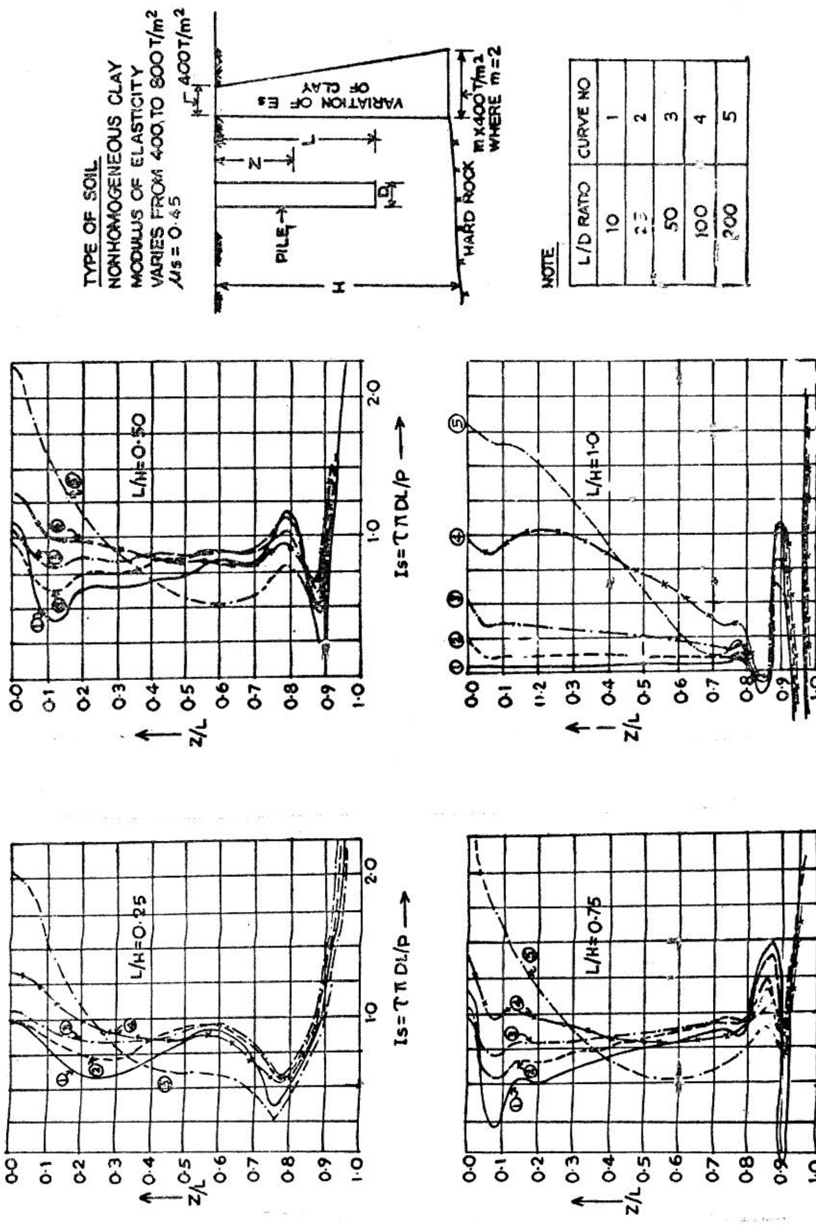

FIGURE 5 Variation of nondimensional influence factor for shear stress (I_s)

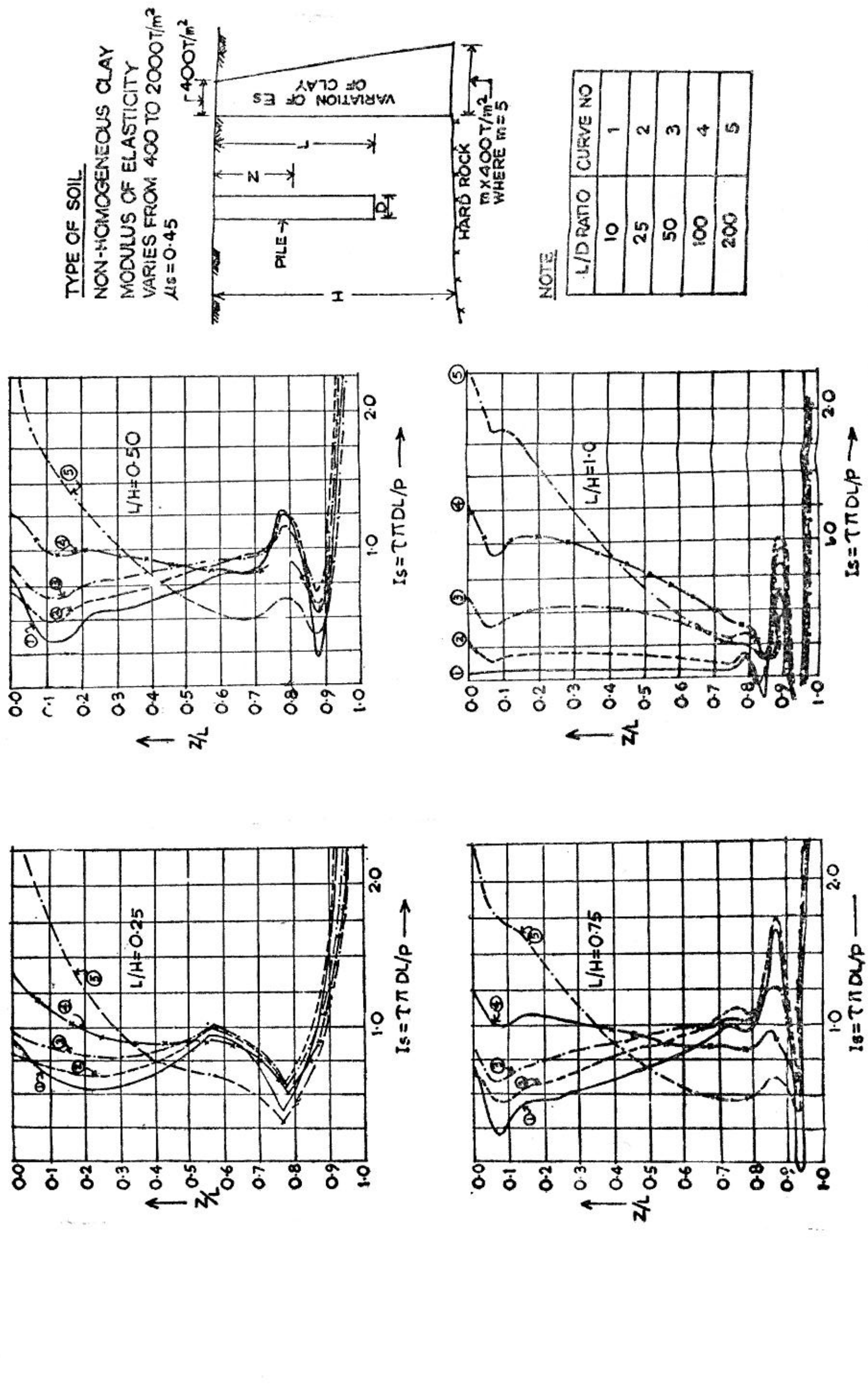

FIGURE 6 Variation of nondimensional influence factor for shear stress (I_s)

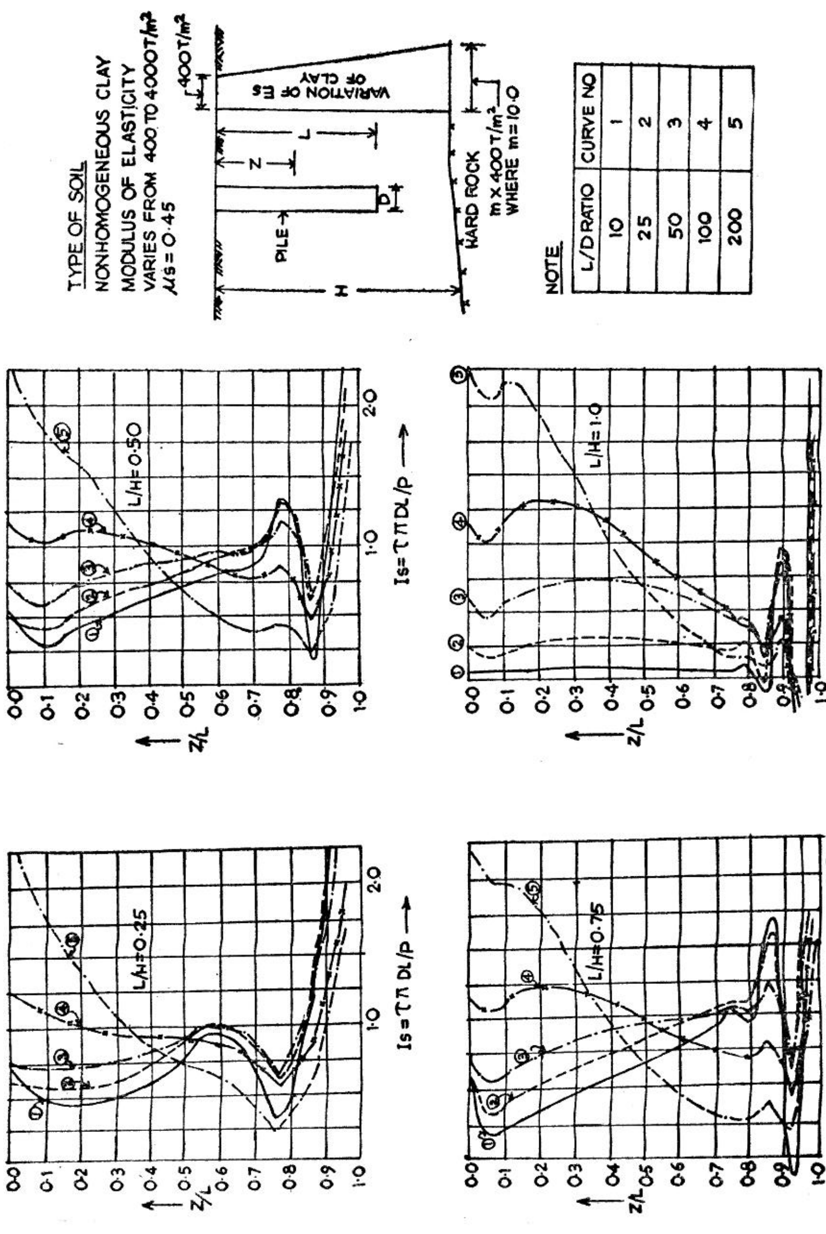

FIGURE 7 Variation of nondimensional influence factor for shear stress (I_s)

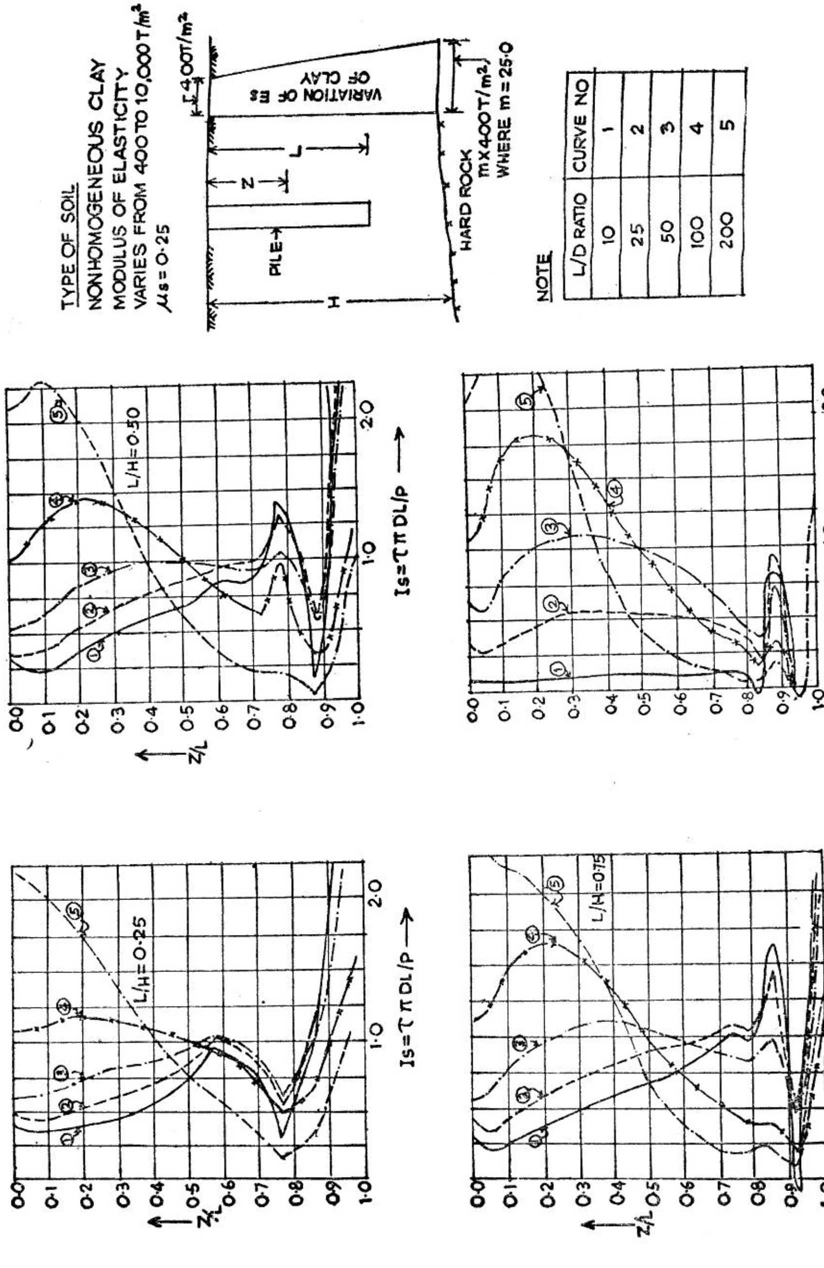

FIGURE 8 Variation of nondimensional influence factor for shear stress (I_s)

(*i*) In all the cases shear stress (I_s) at the pile tips ($Z/L = 1$) is much larger as compared with shear stresses at the pile top; though the shear stresses at the pile top are considerably large in comparison with the shear stresses over the intermediate portion of the shaft. As the curves represent the state of shear for the load (P) corresponding to the straight portion of load settlement curves for the pile-soil systems (i.e., $P < P_1$; where P_1 is the load at which it deviates from assumed linearity), we may conclude that at $P = P_1$, the shear stress at the pile tip would reach the state of limiting equilibrium. This means the shear failure in the pile-soil system, would begin from the pile tips.

(*ii*) As "*m*" increases, in case of each L/H, the shear stresses in the upper region of the pile shaft reduces and in the lower region increases. The maximum reduction and the maximum increase are observed respectively at the top and the tip of the piles.

Influence of L/H

From the figures, it may be observed that the influence of L/H on variation of I_s for all values of "*m*" is more marked in thc lower region of the pile shaft. Further it may be noted that this influence becomes more and more pronounced as "*m*" increases.

In all the cases minimum shear stress zone lies between top maximum shear and bottom maximum shear stresses zones, but as L/H increases, the minimum shear zone shifts towards bottom. Again the value of minimum shear stress decreases as L/H increases and it takes up negative value at $L/H = 1.0$.

In view of the above discussions and the curves presented in Figures 4 to 8, it may be concluded that the variation of shear stress over the pile shaft is significantly influenced by both "*m*" and L/H.

Base Load

The normal stress "σ" transferred through the pile base was determined through the normal stresses over the interface between the pile base and the soil. From Figure 9 it may be noted that all the pile-soil systems, had only one interface element at the pile base, hence only two values of "σ", one for each Gaussian point (Figure 9) were available. Taking their

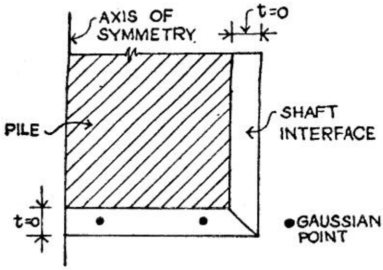

FIGURE 9 Pile-soil system interface

average (σ_b) as the intensity of the stress transferred through the base, "p" the percentage of the applied load (P) transferred through the pile base was computed as under

$$p = \frac{\sigma_b \times \pi/4 \times d^2}{P} \times 100$$

The values of "p" (rounded off) for various pile soils system are presented in Table 2 to Table 6.

TABLE 2

Values of "p" for $L/d = 10$

L/H	m				
	1	2	5	10	25
0.25	4	7	7	8	9
0.50	6	8	10	10	11
0.75	10	10	11	12	12
1.00	74	74	74	74	74

TABLE 3

Values of "p" for $L/d = 25$

L/H	m				
	1	2	5	10	25
0.25	2	2	3	3	3
0.50	2	3	4	4	4
0.75	3	4	5	5	5
1.00	58	58	56	52	50

TABLE 4

Values of "p" for $L/d = 50$

L/H	m				
	1	2	5	10	25
0.25	1	1	1	1	1
0.50	1	1	2	2	2
0.75	1	2	2	2	2
1.00	42	40	38	36	36

TABLE 5

Values of "p" for $L/d = 100$

L/H	m				
	1	2	5	10	25
0.25	1	1	1	1	1
0.50	1	1	1	1	1
0.75	1	1	1	1	1
1.00	30	30	26	24	22

TABLE 6

Values of "p" for $L/d = 200$

L/H	m				
	1	2	5	10	25
0.25	0	0	0	1	1
0.50	1	1	1	1	1
0.75	1	1	1	1	1
1.00	20	16	15	15	14

It may be concluded that, only a small percentage of the applied load gets transferred through the base except in the case of full penetration. Moreover as the pile becomes more slender, the base load decreases.

Settlements

The settlements (S) in metres, suffered by the pile tops are presented in Table 7 to Table 11.

TABLE 7

Settlements of pile tops for $L/d = 10$

L/H	m				
	1	2	5	10	25
0.25	0.0584	0.0455	0.0309	0.0205	0.0105
0.50	0.026	0.0192	0.011	0.0065	0.0031
0.75	0.014	0.0099	0.005	0.00288	0.0014
1.00	0,00036	0 000356	0.00035	0.000349	0.0003

TABLE 8

Settlements of pile tops for $L/d = 25$

L/H	m				
	1	2	5	10	25
0.25	0.1180	0.0657	0.0456	0.0316	0.0181
0.50	0.0403	0.0266	0.0164	0.0106	0.00598
0.75	0.0225	0.0152	0 0085	0.00536	0.00315
1.00	0.00196	0.00194	0.00188	0.00179	0.00154

TABLE 9

Settlements of pile tops for $L/d = 50$

L/H	m				
	1	2	5	10	25
0.25	0.3211	0.116	0.0773	0.0549	0.0348
0.50	0.083	0.0396	0.0258	0.0184	0.0123
0.75	0·038	0.0216	0.0137	0.00994	0.00689
1.00	0.0072	0.0068	0.00626	0.0056	0.00445

TABLE 10

Settlements of pile tops for $L/d = 100$

L/H	m				
	1	2	5	10	25
0.25	1.122	0.309	0.1935	0.136	0.089
0.50	0.2488	0.0864	0.0577	0.0436	0.031
0.75	0,096	0 0425	0.0298	0.0235	0.0174
1.00	0.022	0 0205	0.01812	0.0153	0.0116

TABLE 11

Settlements of pile tops for $L/d = 200$

L/H	m				
	1	2	5	10	25
0.25	4.288	1.065	0.6365	0.4327	0.2685
0.50	0.891	0.265	0.172	0.127	0.0872
0.75	0.316	0.120	0.0839	0.0653	0.0481
1.00	0.0848	0.065	0.0514	0.0417	0.0308

It may be concluded that, the settlements are significantly influenced by both "m" and L/H; and further that "s" decreases with increase in L/H and increase in "m"

Settlements can be represented through non-dimensional settlement parameters I_s and I_b, where

$$I_s = \frac{E_s \, . L \, . S}{P} \text{ and } I_b = \frac{E_p \, . A_b \, . S}{P \times L}$$

E_s = Mod of Elasticity of soil.

E_p = Mod of Elasticity of pile.

P = Axial load.

L = Length of pile.

A_b = Area of pile base

S = Settlement.

In view of the fact that "E" of the soil mass increases with depth, it is obvious that "I_b" would permit a more convenient presentation. In Figure 10 and Figure 11, plots of I_b Vs L/H for various values of "m" are presented. Here L/H is plotted on natural scale, whereas "I_b" represented on log scale. It may be noted that the relationship is linear for the entire range of "m" covered in the analysis.

Case of $L/H = 1.0$. The behaviour of pile soil systems with $L/H = 1$, was radically different from that with $L/H < 1$. It should be noted $L/H = 1$, represent the case of full penetration, wherein, the pile tip would rest directly over the hard unyielding, stratum underlying the cohesive soil stratum. It was expected therefore that the settlement suffered by the pile would be very small and that a very large portion of the applied load would get transferred through the pile base. The results of the analysis

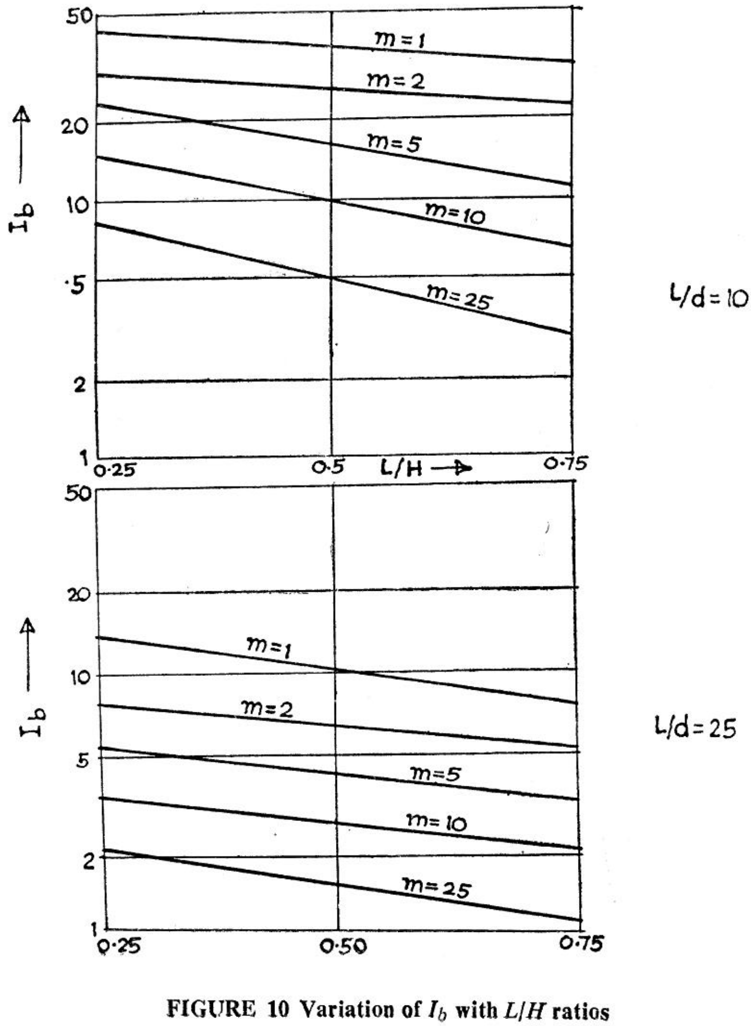

FIGURE 10 Variation of I_b with L/H ratios

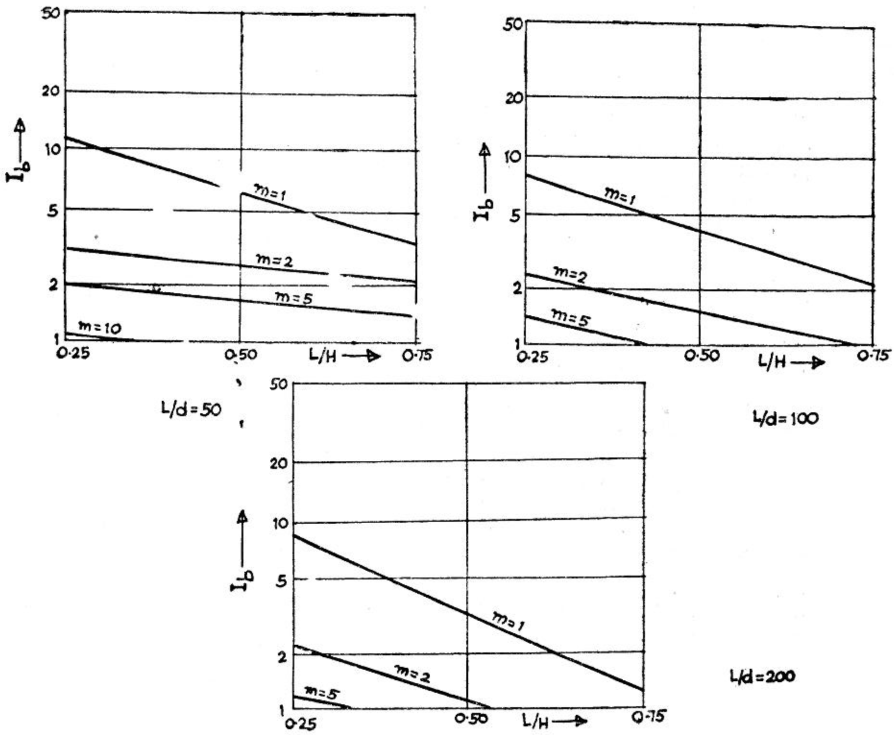

FIGURE 11 Variation of I_b with L/H ratios

confirmed this. For all the values of "m", the settlement was observed to be as small as 0.00035 m and the load transferred at the base of the pile was found to be as high as 74 per cent. (in case of not very slender piles).

The variation of shear stress (I_s) over the pile shaft, representing the 26 per cent of the applied load, was same for all values of "m" except in case of slender piles. It may be noted that excepting a small portion in the vicinity of the pile base, the pile shaft transfers almost uniform intensity of the shear stresses (except in case of very slender piles).

Conclusion and Remarks

As L/H approaches from 0.75 to 1.00 an abrupt increase in the rate of settlement is observed for a specific slenderness ratio of pile. Moreover in case of full penetration, the amount of load transferred at the base shows a tremendous increase. All these indicate that perhaps more detail investigation is necessary before any conclusion can be drawn with regard to the pile behaviour as it approaches firm strata.

Shear stress around pile tip indicates severe stress oscillation.

References

COYLE, H.M. and SULATMAN, I.N., (1967), "Skin friction for steel piles in Sand", *Journal of S.M. div. Proc. A.S.C.E.*, Vol. 93, No SM-6.

COYLE, H.M. and REESE, L C., (1966), "Load transfer for axially loaded piles in clay", *Journal of S.M. div, Proc. A.S.C.E.*, Vol-92, No SM-2, PP. 1-27.

DESHPANDE, V.P., (1974) "Linear Axy-symmetric finite element analysis for critical study of structural response of axially loaded vertical floating piles", Dissertation submitted to University of Poona in partial fulfilment of M E.

ELLISON RICHARD, D., D'APPOLONIA ELLO and THIERS GERALD R. (1971), "Load deformation mechanism for bored piles", *Journal of S.M. div, Proc. A.S.C.E.*, Vol-97, No. SM-4, PP. 661-678.

GOODMAN ET AL, (1968), *Journal of S.M. div, A.S.C.E.*, Vol. 94.

NEIL. S MATTES and HARRY G. POULOS. (1969), "Settlement of single compressible piles', *Journal of the S.M. div, proc. A.S.C.E.*, Vol. 95, No SM-1, PP. 189-207.

REESE L.C. and O'NEILL M.W., (1969), "Field tests of bored piles in beaument clay", *A.S.C.E. annual meeting*, Chicago, preprint 1008, as referred by Woodward R.J. et al, "Drilled pier foundations" Mc Graw Hill book Company, (1972), P. 36.

SAINT V.A., (1976), "Analysis of factors governing structural response of axially loaded pile soil system", Dissertation submitted to University of Poona in partial fulfilment of M.E.