EFFECT OF SIZE AND SHAPE OF FOUNDATION ON ELASTIC COEFFICIENTS IN A LAYERED SOIL MASS

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ABSTRACT

Elastic coefficients (C_u, C_τ, C_ϕ & C_ψ) depend upon the geometry of the foundation and soil properties. One of the most commonly adopted methods to determine the elastic coefficients of soils is to conduct field test on a model foundation, and interpret the value for any other size of area by applying a correction. This approach is fairly justified for homogeneous soils. For layered soils, this relationship is not applicable.

In this paper, an expression has been derived for determining the values of elastic coefficients, in a layered soil mass, for areas different than those for which these have been determined experimentally or otherwise.

Young's modulus 'E' and the load dispersion angle, θ, have been assumed to be constant and the contact pressure to be uniform in each layer. Various shapes considered in this study are (i) rectangular (ii) square and (iii) circular. It is found that the elastic coefficient for square, circular and rectangular shapes is a function of young's modulus, thickness of layer and the ratio of two areas. It is further shown that for homogeneous soil mass, only area ratio is important, as assumed by Barken.

For two layer system, values obtained using the expressions developed in this paper for different ranges of variables are also included.

INTRODUCTION

For the safe design of machine foundation, the determination of natural frequency is important. The various methods for the determination of natural frequency belong to the following categories:-

1) Emperical or Semi-emperical methods

   These include the reduced natural frequency approach of Tschebotarioff[1], relationships given by converse[2] and those recommended in the I.S. Code[3].

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2) Analytical methods

a) Based on theory of elasticity - The analysis given by Reissner[4], Sung[5], Quinlan[6] and others

b) Based on linear spring theory - The analysis given by Barkan[7], Lorenz[8,9], Newcomb[10], Pauw[11] and others

According to linear spring theory, the natural circular frequency of the foundation-soil system is given by

$$W_n = \sqrt{\frac{C_u A}{m}}$$

Where C_u = Coefficient of elastic uniform compression of soil.

A = Area of foundation

m = Mass of vibrating system

The mass (m) includes the mass of the machine, foundation and soil participating effectively in the vibrations. Barkan[12] has shown that the error involved in the determination of vertical natural frequency of a foundation resting on soil surface by neglecting soil mass is not more than 10 percent.

Most widely adopted method to determine coefficient of elastic uniform compression is to conduct an in-situ model block test and to extrapolate the results for prototype foundation[13].

For homogeneous soil using theory of elasticity, Barkan[12] has shown that the coefficient of elastic uniform compression (Cu) is a function of geometry of the foundation and soil properties. The expression obtained by him is

$$C_u = \frac{E \; C_s}{(1-\nu^2)\sqrt{A}}$$

Where C_s = Shape factor of foundation

E = Young's modulus of soil

ν = Poisson's ratio of soil

A = Area

Barkan also obtained an extrapolation formula

$$\frac{C_{up}}{C_{um}} = \sqrt{\frac{A_m}{A_p}}$$

Where

Subscript m and p stand for model and prototype respectively.

In practice, the soils may be stratified having different stiffnesses for each layer. In such cases, use of the above relationship is not justified as it may give erroneous results.

In this paper an expression has been obtained for the proper extrapolation of the results obtained from model block test to prototype in layered soil masses.

THEORETICAL INVESTIGATION

ASSUMPTION

(i) The load on the foundation is dispersed at an angle 'θ' to the vertical (Fig. 1)

(ii) The Young s modulus E_1, E_2 --- E_r ---- E_n are constant within each layer.

(iii) The contact pressure 'p' of the foundation and soil is uniform.

DERIVATION

Consider a footing of plan dimensions a x b ($a > b$) subjected to static stress intensity 'p'. Area of the strip at depth 'Z' below the base of the foundation is given by, Figure 1,

$$A = (a+\alpha z)\ (b+\alpha z)$$

Where $\alpha = 2\tan\theta$

Pressure on this area $= p' = \dfrac{p\ a\ b}{(a+\alpha z)(b+\alpha z)}$

The deformation of the strip of thickness 'dz' at depth, Z, is

$$dw = \frac{p\ a\ b\ dz}{E(a+\alpha z)(b+\alpha z)}$$

Where E = Young's modulus of the material of this layer.

The above expression may be rewritten as

$$dw = \frac{p\ a\ b}{E(b-a)} \left(\frac{dz}{a+\alpha z} - \frac{dz}{b+\alpha z} \right)$$

$$\text{Total deformation} = w \int_{0}^{\infty} dw$$

$$= \frac{pa\,b}{b-a}\left[\int_{0}^{H_1}\left\{\frac{dz}{E_1(a+\alpha z)} - \frac{dz}{E_1(b+\alpha z)}\right\}\right.$$

$$+ \int_{H_1}^{H_1+H_2}\left\{\frac{dz}{E_2(a+\alpha z)} - \frac{dz}{E_2(b+\alpha z)}\right\} + \dots$$

$$+ \int_{H_1+H_2+\dots+H_{r-1}}^{H_1+H_2+\dots+H_r}\left\{\frac{dz}{E_r(a+\alpha z)} - \frac{dz}{E_r(b+\alpha z)}\right\} + \dots$$

$$\left.\int_{H_1+H_2+\dots+H_n}^{\infty}\left\{\frac{dz}{E_n(a+\alpha z)} - \frac{dz}{E_n(b+\alpha z)}\right\}\right] \quad \dots (1)$$

Integrating equation (1) substituting $H_1 = Z_1$, $H_1+H_2 = Z_2$, ...

$H_1+H_2+ \dots +H_r = Z_r$, ... $H_1+H_2+ \dots + H_n = Z_n$ and simplifying,

we get

$$w = \frac{p\,a\,b}{(b-a)\alpha}\left[\frac{1}{E_1}\log_e\left(\frac{b}{a}\right) + \sum_{r=1}^{n-1}\left\{\left(\frac{1}{E_r} - \frac{1}{E_{r+1}}\right)\mathrm{Log}_e\left(\frac{a+\alpha z_r}{b+\alpha z_r}\right)\right\}\right]$$

... (2)

Let C_u = Coefficient of elastic uniform compression for the layered medium under consideration, then from definition

$$C_u = \frac{\text{stress intensity at the base of footing}}{\text{elastic compression of soil below the base}} = \frac{p}{w}$$

$$C_u = \frac{(b-a)\alpha}{ab\left[\frac{1}{E_1}\log_e\left(\frac{b}{a}\right) + \sum_{r=1}^{n-1}\left\{\left(\frac{1}{E_r} - \frac{1}{E_{r+1}}\right)\mathrm{Log}_e\left(\frac{a+\alpha z_r}{b+\alpha z_r}\right)\right\}\right]} \quad ..(3)$$

If a_m and b_m $(a_m > b_m)$ are the dimension of model and a_p and b_p $(a_p > b_p)$ are dimension of prototype. Then the coefficient of elastic uniform compression for model and prototype from equation (3) is given by

$$C_{um} = \frac{(b_m - a_m)\alpha}{a_m b_m \left[\frac{1}{E_1}\log_e\left(\frac{b_m}{a_m}\right) + \sum_{r=1}^{n-1}\left\{\left(\frac{1}{E_r} - \frac{1}{E_{r+1}}\right)\log_e\left(\frac{a_m + \alpha z_r}{b_m + \alpha z_r}\right)\right\}\right]} \quad \cdot\cdot (4)$$

$$C_{up} = \frac{(b_p - a_p)\alpha}{a_p b_p \left[\frac{1}{E_1}\log_e\left(\frac{b_p}{a_p}\right) + \sum_{r=1}^{n-1}\left\{\left(\frac{1}{E_r} - \frac{1}{E_{r+1}}\right)\log_e\left(\frac{a_p + \alpha z_r}{b_p + \alpha z_r}\right)\right\}\right]} \quad \cdot\cdot (5)$$

To establish relationship between C_{up} and C_{um} divide equation (5) by equation (4)

$$\frac{C_{up}}{C_{um}} = \frac{(b_p - a_p)}{(b_m - a_m)} \frac{A_m}{A_p}\left[\frac{\frac{1}{E_1}\log_e\left(\frac{b_m}{a_m}\right) + \sum_{r=1}^{n-1}\left\{\left(\frac{1}{E_r} - \frac{1}{E_{r+1}}\right)\log_e\left(\frac{a_m + \alpha z_r}{b_m + \alpha z_r}\right)\right\}}{\frac{1}{E_1}\log_e\left(\frac{b_p}{a_p}\right) + \sum_{r=1}^{n-1}\left\{\left(\frac{1}{E_r} - \frac{1}{E_{r-1}}\right)\log_e\left(\frac{a_p + \alpha z_r}{b_p + \alpha z_r}\right)\right\}}\right] \quad (6)$$

Equation 6 describes a general relationship between coefficient of elastic uniform compression C_{up} and C_{um}, for area A_p and A_m respectively for an n-layered soil system with each layer defined by constant modulus of elasticity E_r within that layer of thickness H_r, where r is any positive integer.

A few particular cases of general interest will now be considered:

(1) Footings of dis-similar shape on homogeneous deposit.

In this case $E_1 = E_2 = \ldots = E_r = \ldots = E_n$,

and $a_m \neq b_m$, $a_p \neq b_p$ and $\frac{a_m}{b_m} \neq \frac{a_p}{b_p}$, We get from

equation (6)

$$\frac{C_{up}}{C_{um}} = \frac{(b_p - a_p)}{(b_m - a_m)} \quad \frac{A_m}{A_p} \times \frac{\log_e \left(\frac{b_m}{a_m} \right)}{\log_e \left(\frac{b_p}{a_p} \right)} \qquad \ldots (7)$$

The above expression accounts for shape effect of the footing ($\frac{a}{b}$), and is independent of the numerical value of '$\propto$'

(ii) Footings of similar shape on homogeneous deposit.

$$E_1 = E_2 = E_r = \ldots = E_n \quad \text{and} \quad a_m \neq b_m, a_p \neq b_p \quad \text{and} \quad \frac{a_m}{b_m} = \frac{a_p}{b_p}$$

substituting these values in equation 5, we get,

$$\frac{C_{up}}{C_{um}} = \sqrt{\frac{A_m}{A_p}} \qquad \ldots (8)$$

This is the same expression as obtained by Barkan[12] from the theory of elasticity.

(iii) Square footings on non-homogeneous deposit,

$$E_1 \neq E_2 \neq \ldots \neq E_r \neq \ldots \neq E_n \quad \text{and} \quad a_m = b_m \ , \ a_p = b_p \ ,$$

equation (6) becomes indeterminate. Therefore, starting from ab-initio, We get,

$$\frac{Cup}{Cum} = \frac{A_m}{A_p} \left[\frac{\frac{1}{E_1 a_m} + \sum_{r=1}^{n-1} \left\{ \left(\frac{1}{E_r} - \frac{1}{E_{r+1}} \right) \left(\frac{1}{a_m + \propto z_r} \right) \right\}}{\frac{1}{E_1 a_p} + \sum_{r=1}^{n-1} \left\{ \left(\frac{1}{E_r} - \frac{1}{E_{r+1}} \right) \left(\frac{1}{a_p + \propto z_r} \right) \right\}} \right] \qquad \ldots (9)$$

For circular footings, the solution can be obtained by substituting 'd' for 'a' in equation (9) above, where 'd' is the diameter of circular footing.

(iv) Square footing on homogeneous deposit:- In this case

$$E_1 = E_2 = \ldots E_r = \ldots = E_n \quad \text{and} \quad a_m = b_m \ , \ a_p = b_p$$

Substituting the values in equation 9, we get

$$\frac{C_{up}}{C_{um}} = \sqrt{\frac{A_m}{A_p}} \qquad \ldots (10)$$

Equation (10) and (8), are identical as should be expected.

NUMERICAL RESULTS AND DISCUSSION

For proper understanding the effect of each variable on the ratio of coefficients of Elastic Uniform Compression of prototype, to that of model, influence of each variable has been evaluated numerically for two layer system within physically possible range of the particular variable listed below:

a) Dispersion angle $25^\circ - 65^\circ$

b) $a_m/b_m = 1 \quad a_p/b_p = 1-5$

c) $E_1/E_2 = 0.5 - 20$

d) $a_p/a_m = 4 - 20$

e) $\frac{Z_1}{a_m} = 0 - 100$

Effect of Dispersion Angle

Figure 2 shows a plot of C_{up}/C_{um} versus dispersion angle for a typical case of $Z_1/a_m = 10, a_p/a_m = 10$ and for square footings. Different curves are for $\frac{E_1}{E_2}$ varying from 0.5 - 10.

It will be seen that the variation in C_{up}/C_{um} with 'θ' is not large. Hence, an average value of 45° has been adopted in all subsequent computations.

Effect of Ratio of Length to Breadth of Footing

Figure 3 is a plot of $\frac{C_{up}}{C_{um}}$ versus a_p/b_p for $\theta = 45^\circ$

$\frac{A_p}{A_m} = 10$, $a_m/b_m = 1$ and $\frac{E_1}{E_2}$ varying from 0.5 to 20. It will be observed that C_{up}/C_{um} does not alter much with a_p/b_p. Similar trends were seen with other values of variables listed above. Hence the effect of a_p/b_p was disregarded in subsequent analysis and only square footings have been considered.

Effect of Thickness of Top Layer

Figure 4 is a plot of $\frac{C_{up}}{C_{um}}$ versus $\frac{Z_1}{a_m}$ (ratio of thickness of top layer to larger dimension of the model), for E_1/E_2 varying from 0.5 - 20 for square footings (equation 8), & for $a_p/a_m = 10$.

If a soft layer overlies a stiff layer, $\frac{C_{up}}{C_{um}}$ is shown by curve 1. It will be seen that with increasing depth (or Z_1/a_m), beyond Z/a_m of about 1, the ratio decreases and tends to a final value of 0.10, which will be obtained for a homogeneous soil deposit. Upto Z_1/a_m 1, $\frac{C_{up}}{C_{um}}$ increases at a rapid rate from 0.10 to approximately, 0.143.

Fig 5a, b and c shows the pressure bulbs of model foundation of 1m x 1m size and prototype of 10m x 10m. The thickness of top (soft) layer has been considered to be 0.5m, 1.0m and 4m respectively, Corresponding to $\frac{Z_1}{a_m}$ of 0.5, 1 and 4. Value of C_{um} in case 'a' depends upon both the top and bottom layer while in case 'b' it depends more on the top layer. In case 'c' it depends entirely on the top layer. C_{up}, on the other hand depends upon both the layers in all the three cases, But in case 'a', it depends primarily on stiff layer while the influence of top layer becomes gradually more pronounced in 'b' and 'c'.

Qualitatively, it is easy to see that C_{um} in 'b' decreases at a faster rate as compared to C_{um} in 'a' while C_{up} in 'b' decreases at a smaller rate compared to C_{up} in 'a'. Hence C_{up}/C_{um} increases as $\frac{Z_1}{a_m}$ increases from 0.0 to 1.0.

Now C_{um} in 'c' is probably not much different than C_{um} in 'b'. While C_{up} in 'c' decreases at an increasing rate as compared to C_{up} in 'b'. Hence $\frac{C_{up}}{C_{um}}$ decreases as $\frac{Z_1}{a_m}$ increases beyond some characteristic value. This is reflected by curve 1 in Figure 4.

If a stiff layer overlies a soft layer, reverse trends are observed.

It will be seen that for very large values of $\frac{Z}{a_m}$ (say 60) and for $\frac{E_1}{E_2} = 0.5$ and 5, the $\frac{C_{up}}{C_{um}}$ equals o.106 and 0.073 respectively. The difference in the values being 6% and 27% respectively when compared with 0.10 (for homogeneous case). This shows that the effect of soft layer beneath a stiff layer is felt to a larger depth than the effect of stiff layer beneath a soft layer.

Figure 6 is a plot of $\frac{C_{up}}{C_{um}}$ versus scale ratio a_p/a_m for square footings for $\frac{E_1}{E_2}$ varying from 0.5 - 20. As the scale ratio increases, $\frac{C_{up}}{C_{um}}$ decreases.

RELATION BETWEEN C_u, C_τ, C_ϕ and C_ψ

The relation between C_u, C_τ, C_ϕ, and C_ψ given by Barkan[12] is assumed to hold good even for layered soil mass, because these relations are obtained by him after conducting number of field experiments.

The relationships are:

$$C_\tau = 0.5\ C_u \quad \ldots (11)$$

$$C_\phi = 1.73\ C_u \quad \ldots (12)$$

and

$$C_\psi = 0.75\ C_u \quad \ldots (13)$$

Where C_τ = Coefficient of elastic uniform shear of soil.

C_ϕ = Coefficient of elastic non-uniform compression of soil.

C_ψ = Coefficient of elastic non-uniform shear of soil.

APPLICATION TO FIELD TEST DATA

To obtain the elastic coefficient required for the design of Forge hammer foundation, Jamuna auto-industries, Yamunanagar, field investigations[14] were carried out by the Earthquake School. Cyclic plate load test was carried out using 0.3m x 0.3m steel plate. From this test the coefficient of elastic uniform compression obtained was 21000 t/m^3. In order to obtain the subsurface condition, soil exploration and standard Penetration test were carried out and details of soil conditions and standard penetration test results are shown in Fig 7. The soil exploration and penetration test were carried out up to depth of 6m only.

Standard penetration results indicates that the stiffness of soil is not uniform with depth. It shows average standard penetration value is 20 up to 2.74m depth and average penetration, value of 14 below this depth. This indicates stiff layer overlying soft layer.

Assuming Standard penetration values to be proportional to Young's modulus and assuming the same standard penetration value exists below 6m depth, we get.

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{20}{14}$$

The design foundation dimension of the forge hammer is

$$a_p = 6.5 \text{ m}$$

$$b_p = 5.7 \text{ m}$$

Substituting the value of $Z_1 = 2.74$m, $a_m = b_m = 0.3$m, $a_p = 6.5$m, $b_p = 5.7$m, $\theta = 45°$ and $E_1/E_2 = 20/14$ in equation for two layer system we get:

$$\frac{C_{up}}{C_{um}} = (b_p - a_p)\left[\frac{A_m\left\{\frac{1}{a_m} + \left(\frac{E_1}{E_2} - 1\right)\left(\frac{1}{a_m + \propto z_1}\right)\right\}}{A_p\left\{\log_e\left(\frac{b_p}{a_p}\right) + \left(1 - \frac{E_1}{E_2}\right)\log_e\left(\frac{a_p + \propto z_1}{b_p + \propto z_1}\right)\right\}}\right] \quad \ldots (14)$$

$$= (6.5-5.7)\left(\frac{0.3x0.3}{6.5x5.7}\right)\left[\frac{\frac{1}{0.3} + \left(\frac{20}{14} - 1\right)\left(\frac{1}{0.3+2 \times 2.74}\right)}{\text{Log}_e\left(\frac{5.7}{6.5}\right) + \left(1 - \frac{20}{14}\right)\log_e\left(\frac{6.5+2x2.74}{5.7+2x2.74}\right)}\right]$$

$$= 0.0411$$

$$C_{up} = 0.0411 \text{ Cum}$$

$$= 0.0411 \times 21{,}000 \text{ t/m}^3$$

$$= 868 \text{ t/m}^3$$

If it is assumed homogeneous soil mass.

$$C_{up} = \sqrt{\frac{A_m}{A_p}} \text{ Cum}$$

$$= \sqrt{\frac{0.3 \times 0.3}{6.5 \times 5.7}} \times 21{,}000 \text{ t/m}^3$$

$$= 1042 \text{ t/m}^3$$

Difference in Cu = 1042 - 868

= 174 t/m^3

CONCLUSIONS

Expressions for ratio of coefficients of elastic uniform compression of a prototype to model in a layered medium have been derived and particular cases of 2-layered system has been solved in detail. It has been shown that

1. For proper extrapolation of coefficient of elastic uniform compression of soil from model block test to prototype, the sub soil exploration and deformation characteristic of each layer of soil is essential.

2. The percentage error involved in using the relation $C_{up}/C_{um} = \sqrt{\frac{A_m}{A_p}}$ is maximum for higher scale ratio and higher stiffness ratio.

3. The load dispersion angle can be suitably assumed as 45^o and length to breath ratio can be neglected.

NOTATIONS

SYMBOL		DESCRIPTION
A	-	Area.
A_m & A_p	-	Area of model and prototype respectively.
a	-	Length of foundation.
a_m & a_p	-	Length of model and prototype foundation.
b	-	Breadth of foundation.
b_m & b_p	-	Breadth of model and prototype foundation.
Cu	-	Coefficient of elastic uniform compression of soil.
C_{um} & C_{up}	-	Coefficient of elastic uniform compression of soil for A_m and A_p respectively.
C_s	-	Shape factor of foundation.

SYMBOL		DESCRIPTION
C_τ	-	Coefficient of elastic uniform shear of soil.
C_ϕ	-	Coefficient of elastic non-uniform compression of soil.
C_ψ	-	Coefficient of elastic non-uniform shear of soil.
E	-	Young's modulus of soil.
$E_1, E_2 \ldots E_r \ldots E_n$	-	Young's modulus of soil for layer 1,2...r...n respectively.
e	-	Base of natural logrithem.
$H_1, H_2 \ldots H_r \ldots H_n$	-	Thickness of layer 1,2 ... r ... n respectively.
m	-	Mass of vibrating system.
p	-	Uniform stress intensity at the contact, surface of soil and foundation.
$Z_1, Z_2 \ldots Z_r \ldots Z_n$	-	Depth from contact surface to the bottom of layer 1, 2 ... n respectively.
ν	-	Poissons ratio of soil.
θ	-	Load dispersion angle.

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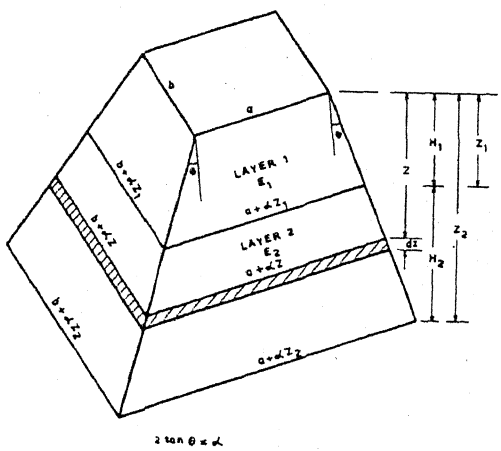


FIG. 1 – LOAD DISPERSION IN LAYERED SOIL MASS

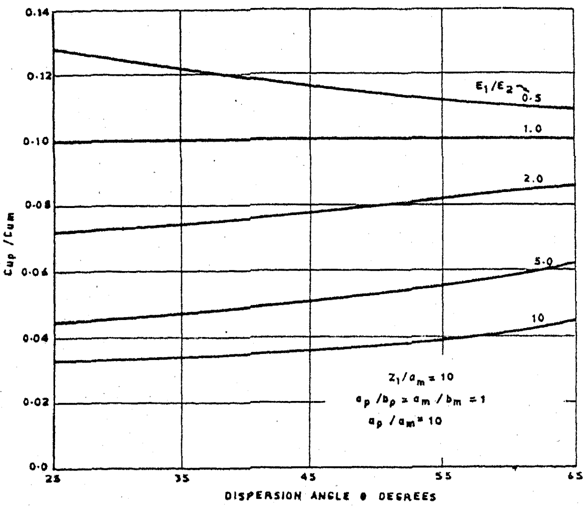


FIG. 2 – Cup/Cum VERSUS θ

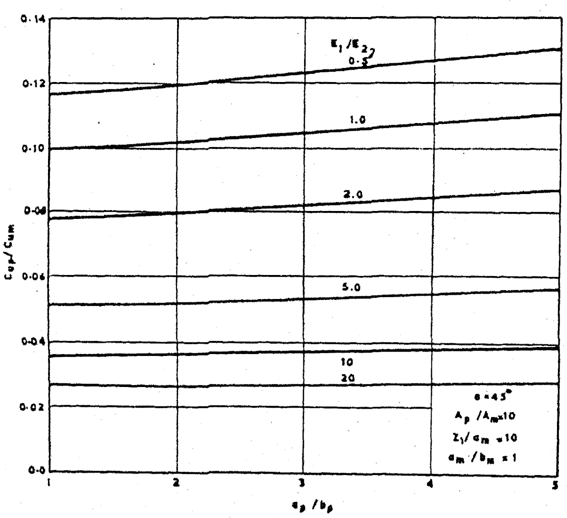


FIG. 3 – C_{up}/C_{um} VERSUS a_p/b_p FOR E_1/E_2=0.5-20

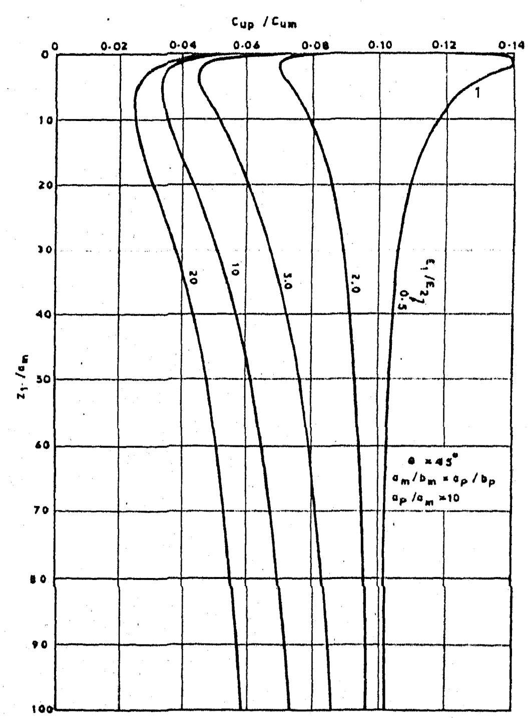


FIG. 4 – Cup /Cum VERSUS Z_1/a_m

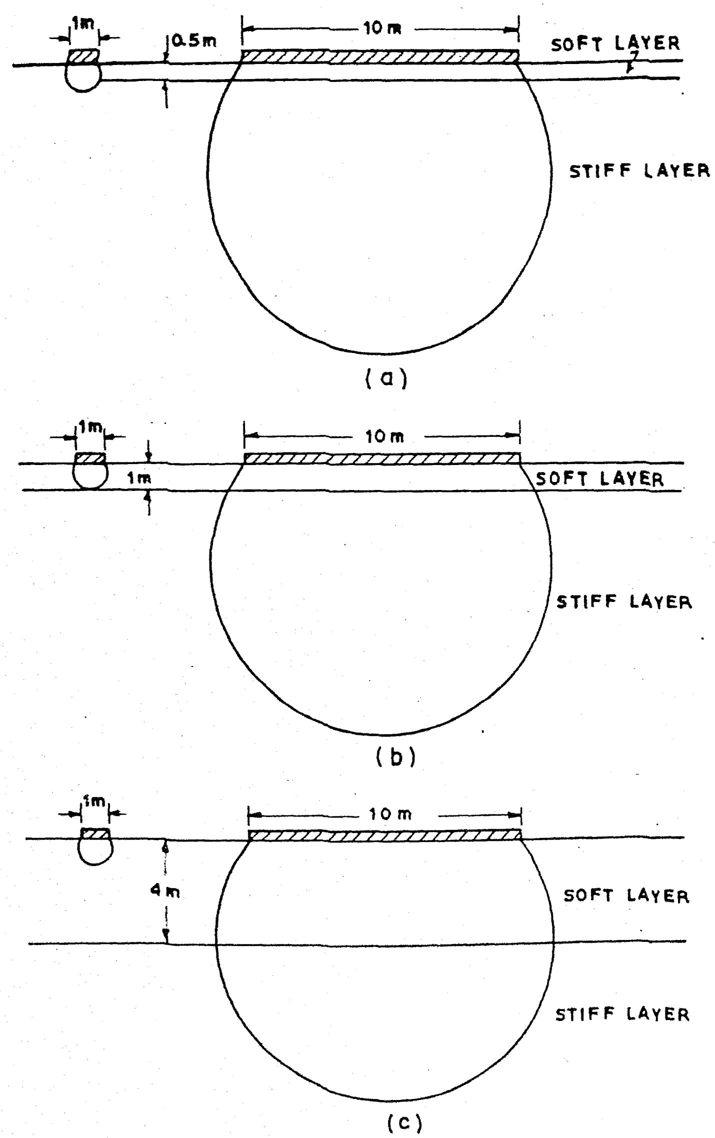


FIG. 5 _PRESSURE BULBS FOR MODEL AND PROTOTYPE FOUNDATION IN LAYERED SOIL MASS

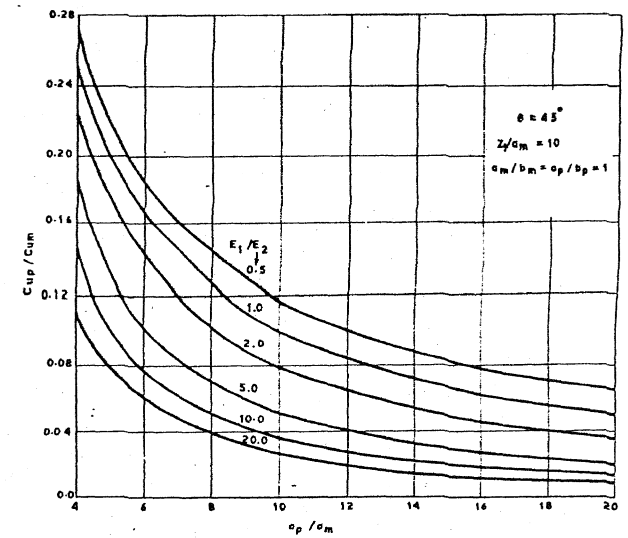
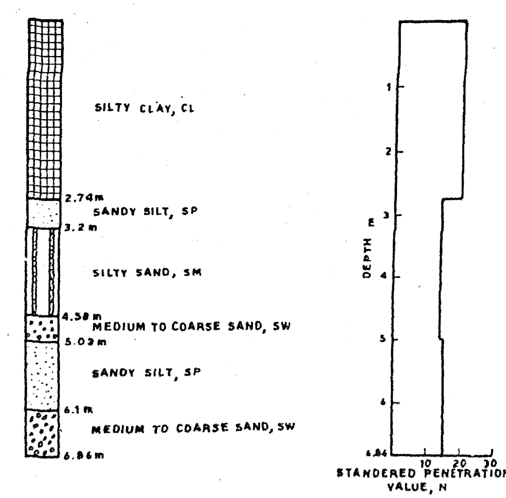


FIG. 6 _ Cup / Cum VS a_p / a_m FOR E_1 / E_2 = 0.5-20



a_ BORING LOG AT SITE

b_STANDERED PENETRATION TEST RESULTS AT SITE

FIG. 7 _ BORING LOG AND SPT DATA FOR FORGING HAMMER SITE