Final Report

NEGATIVE SKIN FRICTION ON PILES

by

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SKIN FRICTION ALONG PILES

Skin friction along piles develops according to the same laws of nature that describe friction between any two bodies. To develop friction, the bodies must tend to move relative to each other. The amount of frictional resistance between the two bodies depends on the normal force (in this case produced by normal effective stress), the coefficient of friction between the two bodies and sufficient shear strain.

1. Positive Skin Friction Only

Positive skin friction along the contact surface of pile and soil develops when the pile tends to settle relative to the surrounding soil. Settlement (compression or consolidation) of the soil after the pile is driven is caused by stresses in the soil produced by the pile.

The pile stresses the soil as shown in Fig. 1. In the general case, the load P on the pile is carried by both the upward skin friction F_p and the tip reaction Q.

2. Negative Skin Friction Only

Negative skin friction develops along the contact surface between pile and soil when the soil settles relative to the pile. When relative soil settlement occurs at all elevations of the pile, then negative skin friction develops along the entire length of the pile as shown in Fig. 2. The forces P and Q are as defined before and F_n is used to denote negative skin friction. This will occur when the pile is driven to rock and the soil surrounding the pile settles after the pile is in place, and the deflection of the pile tip under load is negligible.

3. Both Positive and Negative Skin Friction Acting on the Same Pile at Different Elevations

This case occurs when the relative settlement between pile and soil reverse sign at some depth. The forces on the pile cause the tip to settle or penetrate into the bearing stratum. The point on the axis of the pile where the relative settlement between pile and soil is zero is called the neutral point. Above the neutral point the soil settles more than the pile and produces negative skin friction. Below this point, the pile settles more than the soil and develops positive skin friction. Figure 3 illustrates the forces on a pile driven into firm stratum. The maximum axial force in the pile occurs at the neutral point.

An uneconomical design may result in some cases when the neutral point is neglected and the skin friction is assumed to be negative along the entire pile length. For an accurate analysis it is necessary to locate the neutral point and determine the force in the pile at this point. Presentation of a method for estimating the location of the neutral point will be made after the presentation of the available methods for computing skin friction.

METHODS OF ESTIMATING NEGATIVE SKIN FRICTION

Nine methods of estimating negative skin friction and the resulting downdrag force were found in the literature. Each of them contains some theory, used with strength data for the soil and some empirical quantities.

The nine methods are:

1.	Terzaghi and Peck	(1967)
2.	Garlanger	(1973)
3.	Elmasry	(1963)
4.	Zeevart	(1959)

5. Brinch Hansen (1968)
6. Johannessen and Bjerrum (1968)
7. Buisson, Ahu and Habib (1960)
8. Salas and Belyunce (1965)
9. Poulos and Mattes (1969)

Most of these methods treat the downdrag on single piles. Exceptions are Terzaghi and Peck (1967) and Zeevart (1959) which treat pile groups.

The nine methods were reviewed in two steps. First the theory, assumptions and equations were evaluated for ease of application to field situations and the ease of determining the required soil parameters from standard laboratory tests. Second, the results predicted by each method were compared with published field measurements and with each other. From this evaluation, the methods of Terzaghi and Peck, and Garlanger appear to give reasonable values and are straightforward in application. These two methods will be described here in detail. An approximate method based on statics is also presented.

1. Terzaghi and Peck's Method

A. General

This method was developed for pile groups and yields a value for the total negative skin friction which represents the upper limit of the downdrag force. It is based on the shear strength of the soil and can be also applied to a single pile. The total downdrag force is the result of the perimeter shear developed by the consolidating soil and the weight of the fill between piles, if any.

The total negative skin friction force (F_n) for each pile in a group can be found from the equation:

$$F_n = F_{n1} + F_{n2} \qquad [1]$$

caused by disturbance during driving. When piles are driven to yielding strata above rock, the pile will settle as the negative skin friction develops and a neutral point somewhere in the clay above the firm stratum will develop. The assumption that negative skin friction acts along the entire length of the pile in the consolidating soil is conservative.

2. Garlanger's Method

A. General

Garlanger's method assumes that the negative skin friction at any depth along a single pile is proportional to the effective overburden pressure at that depth and can be computed from the equation:

$$\tau = \beta\sigma'_v \qquad [4]$$

where: τ = negative skin friction at the depth of interest, β = constant of proportionality that includes various correction factors and must be determined experimentally, σ'_v = apparent effective overburden pressure at the depth of interest.

The term $\beta = \alpha \; K \tan \delta$ [5]

where: α = correction factor to account for the reduction in vertical effective pressure due to the transfer of load to the pile by negative skin friction, K = coefficient of lateral earth pressure, δ = friction angle between pile and soil or soil and soil, whichever is less.

The total negative skin friction is given by:

$$F_n = \Sigma \, \bar{D} \, \tau \, dz$$

$$= \int_o^H \bar{D} \, \beta \, \sigma'_v \, dz \qquad [6]$$

$$= \bar{D} \, \beta \times \text{area of effective overburden pressure diagram}$$

where: $\bar{D}$ = perimeter of pile

B. Determination of β

The most reliable method of determining the parameter β, according to Garlanger, is to drive different types of piles into different soils, cause the soil to move relative to the pile, measure the load in the pile at various depths and backfigure the value of β which would correspond to this load distribution, i.e.:

$$\beta = \frac{\Delta P_{1-2}}{\bar{D} \int_{Z_1}^{Z_2} \sigma'_v \, dz} \qquad [7]$$

Alternatively, the shortening of various sections of a pile could be measured and the value of β backfigured from the deformation, i.e.:

$$\beta = \frac{A_p \cdot E_p \cdot \Delta y_{1-2}}{\bar{D} \cdot L_{1-2} \int_{Z_1}^{Z_2} \sigma'_v \, dz} \qquad [8]$$

where:

L_{1-2} = length between elevations Z_2 and Z_1

ΔP_{1-2} = load increment between depths Z_1 and Z_2

A_p = area of cross section of pile

E_p = Young's modulus for pile material

Δy_{1-2} = deflection between section 1 and 2 at depths Z_1 and Z_2

C. Data Required to Use this Method:

1. β value
2. Unit weights for the soil
3. Thickness of different soil layers H (H_1, H_2, etc.)
4. Pore pressures at different elevations
5. Pile cross section, material, length
6. Young's modulus for pile material

7. Instrumented load test to determine β value
8. Water table conditions

D. Assumptions

a) The main assumption is that the negative frictional stress is constantly proportional to the effective overburden pressure of the soil.

b) This value of F_n gives the maximum limit for the total negative skin friction that can be transmitted to the pile from the soil.

Garlanger suggests the following values of β for estimating the total negative skin friction:

Soil	β
Clay	0.20 to 0.25
Silt	0.25 to 0.35
Sand	0.35 to 0.50

The list of β values prepared by Garlanger is in the Appendix.

$$F_n = \beta \times \bar{D} \times A_o \qquad [9]$$

where: A_o = area under the vertical effective pressure diagram above the neutral point. When the pile penetrates layers with different properties the total downdrag force is developed from a summation of the characteristics of each soil above the neutral point. The equation for this case can be written:

$$F_n = \bar{D}[\beta_1 \times A_1 + \beta_2 \times A_2 + - - - -] \qquad [10]$$

where: β_1, β_2, β_3 are the proportionality constants for 1, 2, 3, etc. and A_1, A_2, etc. are the areas under vertical pressure diagrams for the respective layers.

3. An Approximate Method Based on Statics

The total amount of downdrag force experienced by a single pile or pile group is related to the height and extent of the fill placed at the ground surface. A method of estimating the total downdrag force is shown in Fig. 5. This method is based on statics and on approximate stress distribution. The distance L in Fig. 5 equals the length of the pile cap plus the length of the piles. A distance B perpendicular to L can be defined as the width of the pile cap plus the length of the piles. The total downdrag force can be approximated as the weight of fill covering the area B x L. An example illustrating the use of this method is shown in the Appendix.

DISCUSSION OF THE METHODS OF TERZAGHI AND PECK AND GARLANGER

The method of Terzaghi and Peck (T&P) yields a conservative value for the negative skin friction of medium to stiff clays. The (T&P) analysis is based on the shear strength of the soil. Friction along the pile equal to the original shear strength of the soil may not develop due to disturbance of the soil. The soil may displace relative to the pile at a stress which is much lower than the original shear strength. The estimates by this method represent the upper limit, but this approach does usually give approximately correct values for soft clays.

The method of Garlanger appears to give results that are slightly high for soft clays but about the proper downdrag value for medium and stiff clays. The major shortcoming of this approach is the evaluation of the β parameter which must be backfigured from field tests. Limits can certainly be placed on this value depending on the type of soil although the exact value cannot be determined without field tests.

Garlanger's method has been used for single piles only. No field tests have been conducted on pile groups, but a simple straightforward approach to estimating the downdrag force on pile groups can be worked out. The settlement of the soil outside the pile group will transmit the negative skin friction force to the group through the perimeter piles. The downdrag force for each of the perimeter piles can be related to the value for a single pile, thus:

1. Corner piles - three-fourths (3/4) of single pile value
2. Exterior piles - one-half (1/2) of single pile value

This approach is based on the model group shown in Fig. 4 in which all the piles are rigidly tied together with a pile cap. The computations are based on the downdrag forces produced in an isolated pile. The computed forces must be modified to reflect the boundary conditions of the group. As can be seen from Fig. 4, three-fourths of the corner piles and one-half of the exterior piles have downdrag conditions similar to an isolated pile. The additional downdrag force on the corner, exterior and interior piles can be estimated from the total fill directly over the pile group as in the T&P method.

ESTIMATING THE LOCATION OF THE NEUTRAL POINT

1. Significance of the Neutral Point

The neutral point is the position along the pile at which the soil and the pile experience equal settlements. Above this point the soil is settling more than the pile. Below this point the pile settles more than the soil. The force in the pile is greatest at the neutral point.

When an end bearing pile is driven to rock, the neutral point occurs in the soil a negligible distance above the top of rock. Little error is introduced by assuming that the negative skin friction acts along the full length of the pile. For a pile driven into less firm material the neutral point may occur at a considerable distance above the top of the bearing stratum. The assumption that the neutral point occurs at the top of the firm stratum may yield a pile section that is too conservative.

2. Procedure for Finding the Neutral Point

A. General

Locating the neutral point in the soil requires a cut and try procedure that compares the relative displacement of the pile at each point to the settlement of the surrounding soil. The following information is required:

a.) the settlement of the pile tip under load

b.) the elastic shortening of the pile under load

c.) the void ratio versus consolidation pressure curve (e - log p) for the soil

d.) friction characteristics between pile and soil

B. The Steps in Each Trial Are:

a.) Assume the location of the neutral point (for the first trial assume a location at a height above firm stratum of about 10% of the thickness of the consolidating layer.)

b.) Using the overburden effective stress and the β parameter, compute the contact friction stresses along the pile. (When using T&P approach, use shear strength instead of β).

c.) Compute and plot the forces in the pile.

d.) Beginning at the pile tip, plot the displacement of the pile and compare it to the settlement of the soil. The neutral point occurs where downward displacement of the pile equals the settlement of the soil.

e.) Using the neutral point thus located perform another trial until the shift of the neutral point on successive trials is negligible.

C. Discussion

Estimating the location of the neutral point requires a comparison of the relative displacement of pile and soil. The soil displacement can be computed by the usual techniques for compression settlement. The displacement of the pile at various elevations involves both tip displacement and shortening of the pile under compressive forces.

To facilitate the pile computation, a diagram showing the variation of force in the pile with depth should be plotted. This plot is based on the assumed location of the neutral point. The force in the pile will depend on applied load as well as soil and water conditions. The length of the pile is then divided into convenient sections. The shortening of each section can be computed using an average value from the force diagram.

The displacement of the pile tip is related to the tip reaction. The displacement of the tip can be estimated by using a modulus of subgrade reaction which can be determined from a pile load test or estimated from the relative density of the firm stratum. The relative density is often approximated from the standard penetration test or casing blow counts or both. A relation between the relative density and the modulus of vertical subgrade reaction is shown in Fig. 11-8 of the NAVDOCKS DM-7 manual (14), and can be found from the equation:

$$K_{v1} = \frac{350}{80}(D_R - 20) \qquad [11]$$

where: K_{v1} = the modulus of vertical subgrade reaction in tons/ft^3;

D_R = relative density in percent.

The settlement of a deep foundation is computed from: (14)

$$\rho_v = \frac{2Q}{K_{v1}\ (B+1)^2} \qquad [12]$$

where: Q = tip load; ρ_v = tip settlement; B = width or diameter of pile.

The displacement of the pile can now be estimated beginning with the tip settlement then computing the shortening of each pile segment starting from the bottom segment and proceeding up with the equation:

a.) $\Delta Y = \frac{P_z\ Y}{A_p E_p}$ where [13]

P_z = load carried by pile at the corresponding elevation

A_p = area of pile cross section

E_p = Young's modulus for pile material

Y = elemental length of pile

b.) $S = S_o + \Sigma\Delta L$, the deflection of pile at top of pile segment being considered

S_o is the displacement of the pile tip.

REDUCTION OF NEGATIVE SKIN FRICTION

Several techniques are effective in reducing the negative skin friction on a pile and allowing a more economical design. Three of these methods that have been tested in the field are:

1. Bitumen coated steel piles surrounded by a bentonite slurry
2. Concrete pile surrounded by bentonite
3. Electro-osmosis

The most effective reduction of negative skin friction reported has been with bitumen on steel piles. Using this technique Bjerrum et al (13) have succeeded in reducing the negative skin friction by 90%. The steel piles were coated with 80/100 penetration bitumen about 1 mm thick. The possibility of scraping off the coating as the pile was driven through granular fill was eliminated by using a driving shoe that was 10 cm (4 inches) wider than the pile. This oversized driving shoe created an open space between the soil and the pile. A bentonite slurry was placed in the open space around the pile to prevent the soil from collapsing against the pile.

Electro-osmosis has also been found effective in reducing the negative skin friction between steel piles and soil (13). The pile is made the cathode and a metal rod is driven close by as an anode. The voltages required are small (0.6 v. to 2.0 v.) and of the same order of magnitude as the voltage used in cathodic protection. The treatment with electro-osmosis must be continued until the compression of the clay is complete. The method may be economical in situations where cathodic protection is required anyway to prevent corrosion.

APPENDIX

Table I β values collected by Garlanger

Example Problem Using Approximate Method Based on Statics

TABLE I

Empirical Values of β

REFERENCE	PILE TYPE	SOIL CONDITIONS	β
Bjerrum Johannessen & Eide (1969)	Steel Pipe	Silty Clay	.25
	Steel Pipe	Silty Clay	.26
	w/ Bitumen	Silty Clay	.02
	Steel Pipe	Clay	.18
	Steel Pipe	Clay	.23
	w/ Bitumen	Clay	.01
Bjerrum & Johannessen (1965)	Krupp KP24	Marine Clay	.20
Bozozuk & Labrecque (1969)	Steel Pipe	Sand & Silty Clay (N.C. & O.C.)	.20
Brons et al (1969)	Concrete	Cohesive Soil	.24
	w/ Bitumen	Cohesive Soil	.01
	w/ Bentonite	Cohesive Soil	.03
	Concrete	Clay & Sand	.19
Bozozuk (1970)	Steel Pipe	Compacted Sand Fill	.77
	Steel Pipe	Silty Sand	.33
Endo et al (1969)	Steel Pipe (closed end)	Sandy Silt	.35
	Steel Pipe (open end)	Sandy Silt	.20
	" " (battered)	Sandy Silt	.33
	Steel Pipe (closed end friction)	Sandy Silt	.30
Fellenius (1971)	Precast Concrete	Marine Clay	.09
Walker & Darval (1972)	Steel Pipe	Sand	.52
	Steel Pipe	Silty Clay	.23
Gant et al (1958)	Monotube Pile	Clayey Silt & Sand	.33

c.f. Garlanger (7)

Example Problem Using Approximate Method Based on Statics

Conditions

a. Height of fill 10 ft.

b. Unit weight of fill $\gamma_t = 120$ #/ft^3

c. Length of piles through consolidating soil 50 ft.

d. External dimensions of pile group 10 ft. x 10 ft.

Refer to Fig. 4

L = Length of pile through consolidating soil + length of group

= 50 ft. + 10 ft. = 60 ft.

In this case the dimension in the direction perpendicular to this will be the same because the external dimensions of the group form a square.

Downdrag force = Weight of fill in area defined by L x L

= 120 lb/ft^3 x 60 ft. x 60 ft. x 10 ft. = 4320 kips

NOTE: the computed value represents an upper limit. The amount of fill included in the computation can be varied depending on the soil and fill conditions.

LEGEND FOR DIAGRAMS

Figure 1	Positive Skin Friction
Figure 2	Negative Skin Friction
Figure 3	Development of a Neutral Point in the Soil
Figure 4	Contribution of Downdrag Forces in a Pile Group Hatched lines indicate influence from consolidation outside group. White portions of pile indicate downdrag from soil inside group.
Figure 5	Method for Determining the Weight of Fill That Will Develop Downdrag Force

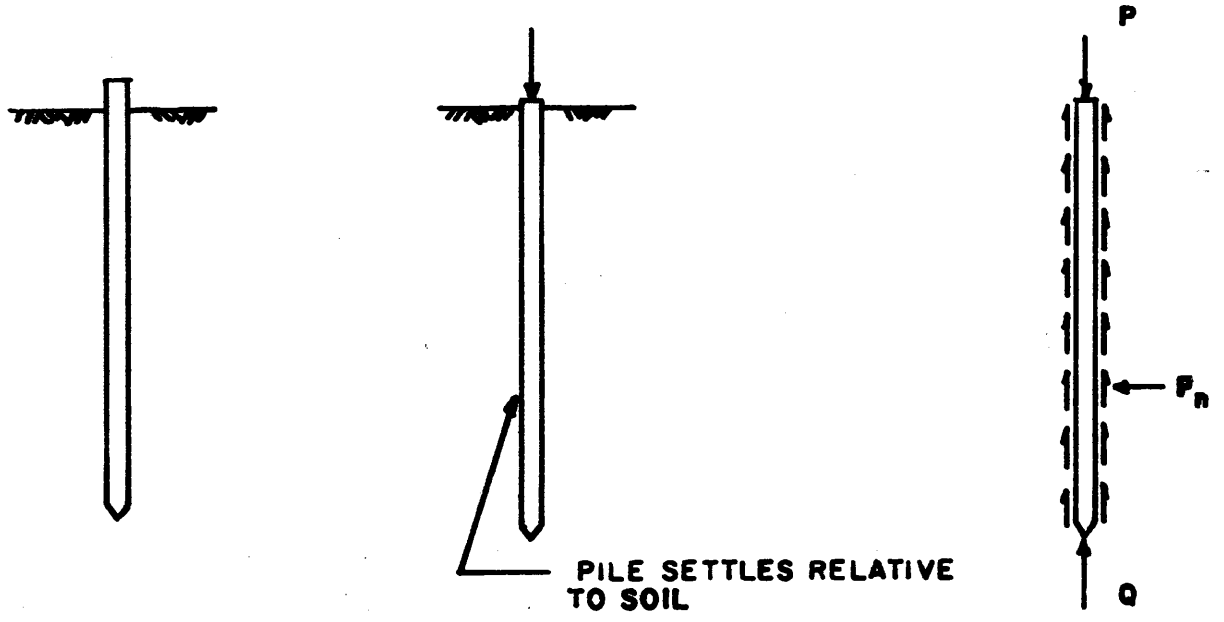

FIG. 1

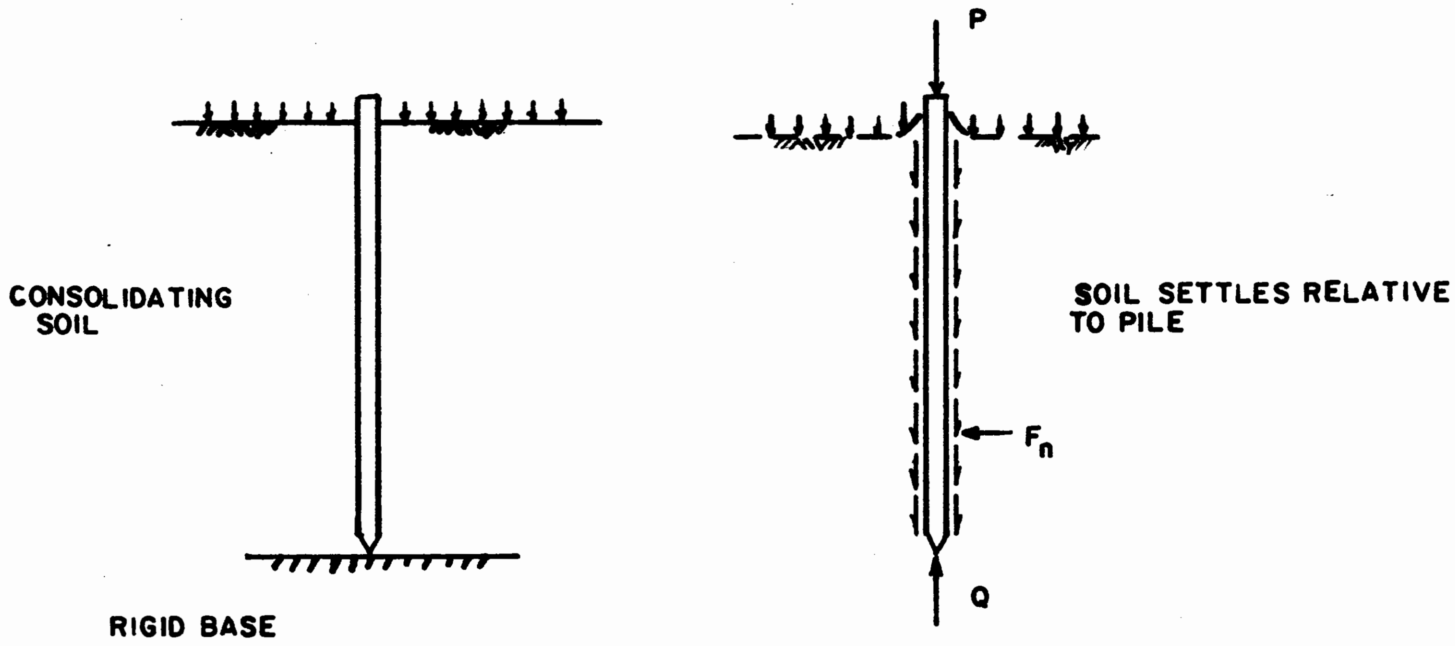
CONSOLIDATING SOIL
RIGID BASE
P
SOIL SETTLES RELATIVE TO PILE
F_n
Q

FIG. 2

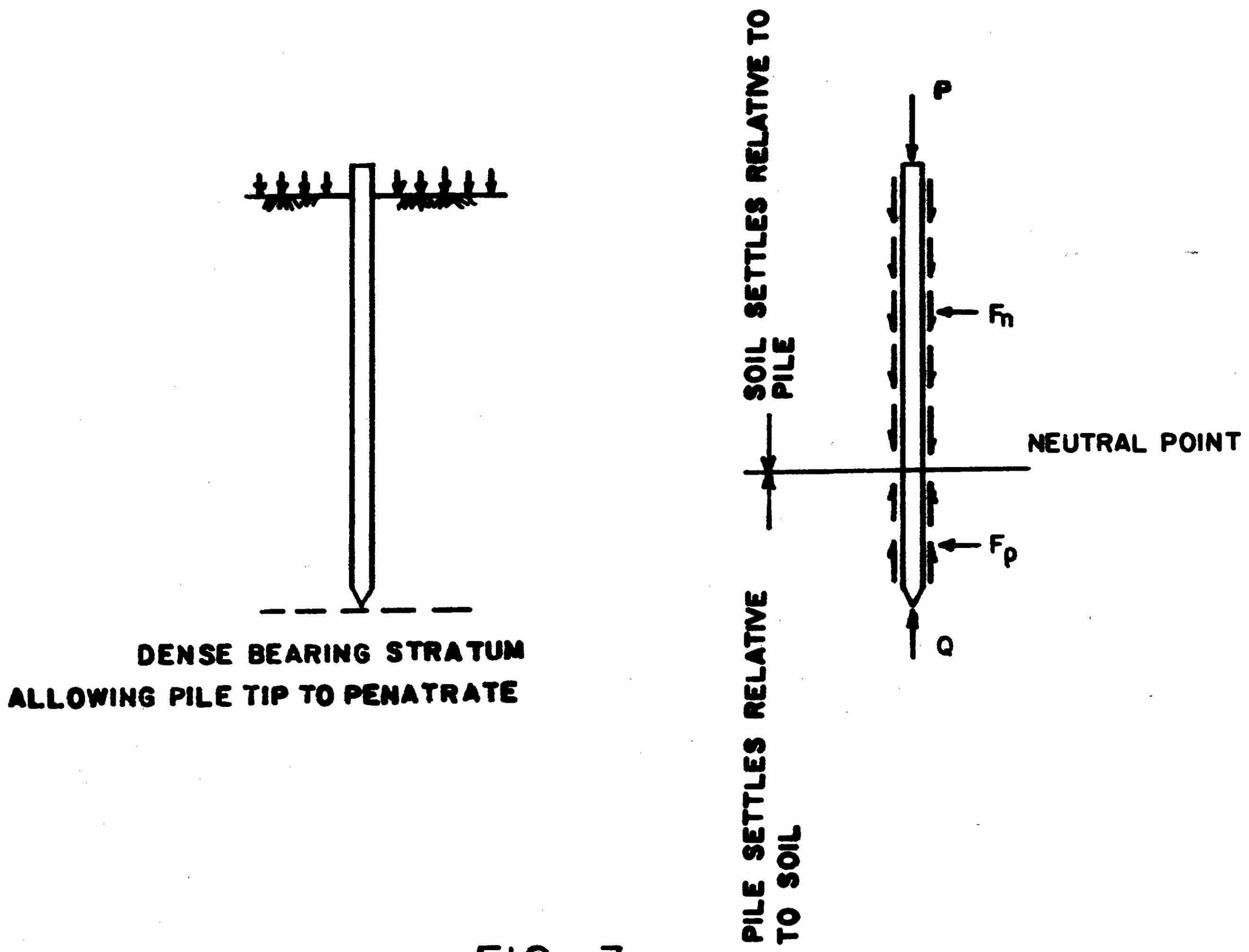
DENSE BEARING STRATUM
ALLOWING PILE TIP TO PENATRATE
SOIL SETTLES RELATIVE TO PILE
PILE SETTLES RELATIVE TO SOIL
P
F_n
NEUTRAL POINT
F_p
Q

FIG. 3

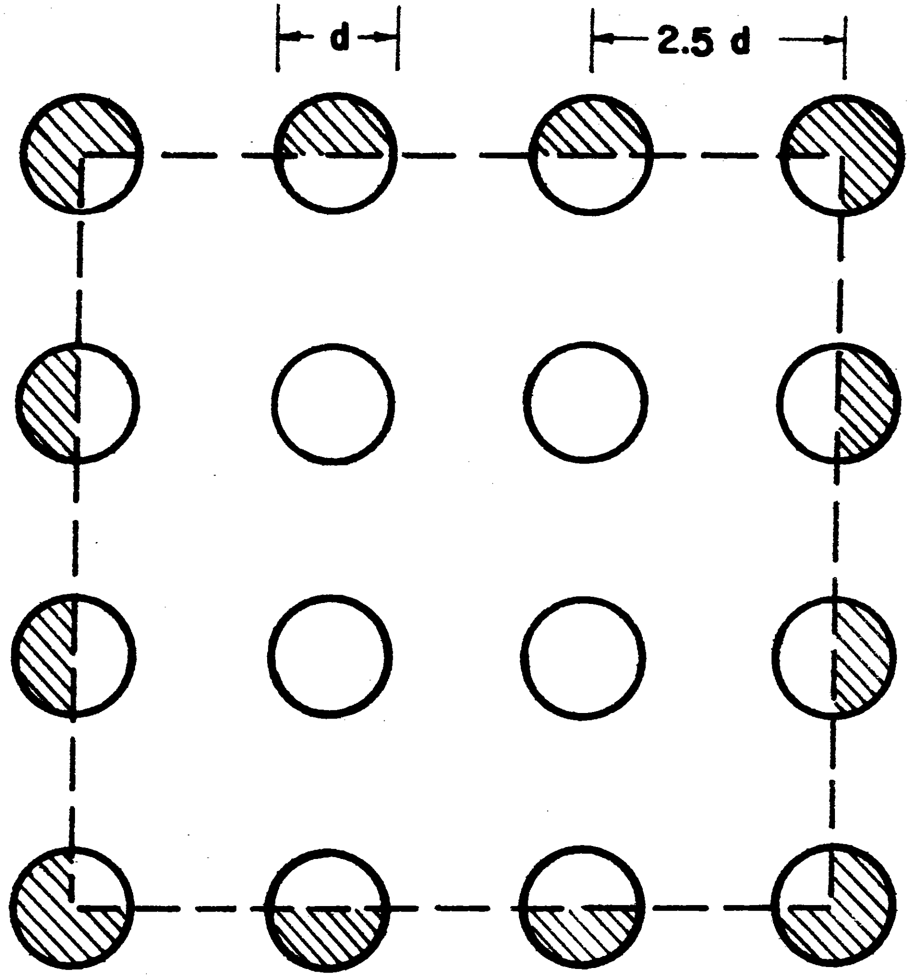

FIG. 4

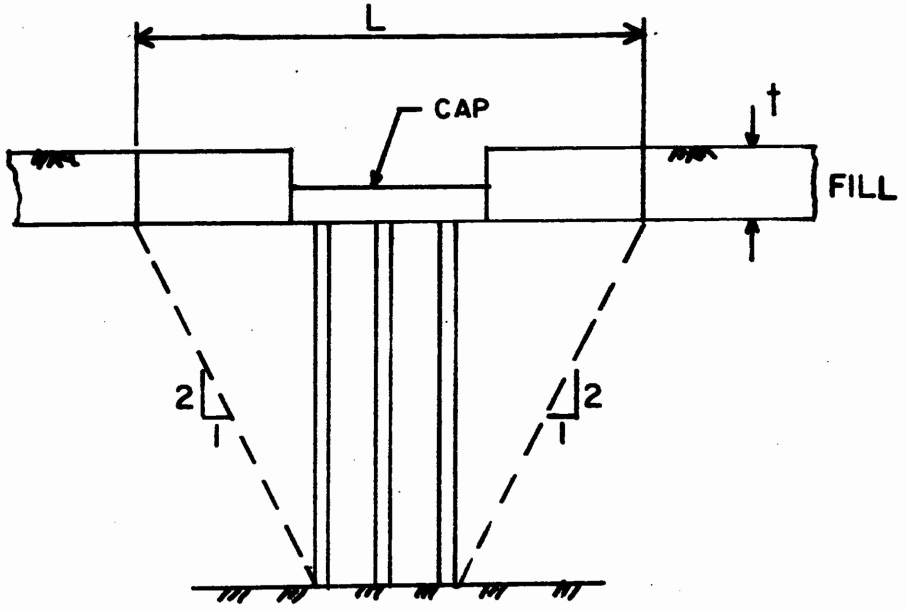

FIG. 5