BEHAVIOR OF NEGATIVE SKIN FRICTION ON MODEL PILES IN MEDIUM-PLASTICITY SILT

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The mobilization of negative skin friction (downdrag) on deep foundations can be so large that either failure or excessive deformation of the structure founded thereon can occur. Yet little information regarding the behavior of the downdrag phenomenon is known. Since full-scale testing of the influence of the large number of variables involved is economically prohibitive, a simulated laboratory experiment has been developed. Results of negative skin friction distribution with increasing soil deformation confirm the validity of the experimental setup. The influence of pile batter, pile group spacing, soil-water content, and pile material on average negative skin friction is investigated. From these test sequences, generalized conclusions are drawn. Various means of preventing negative skin friction from occurring have also been examined, and the use of asphalt coatings on the pile is shown to be quite successful. The influence of asphalt coating viscosity and thickness on average negative skin friction is presented. These curves form the basis for a design method to eliminate the major portion of downdrag on pile foundations.

•THE MAGNITUDE of negative skin friction (downdrag) on deep foundations can be greater than the ultimate capacity of the foundation itself. Even when the capacity of the foundation is not approached, negative skin friction can result in excessive settlement of the foundation and the structure founded on it. Investigation into the behavior of the phenomenon has made relatively little progress and is typified by a wide variety of approaches toward a predictive technique. The Seventh International Conference on Soil Mechanics and Foundation Engineering brought the problem to the attention of many through a specialty session (18) and a state-of-the-art report (6). Verification of any proposed technique to evaluate downdrag magnitude requires test results that are most difficult to obtain in the field because of the extremely long time and expense involved for instrumentation. The alternate to full-scale field testing is scaled-down model tests that can be conducted in the laboratory under controlled conditions. It then becomes possible to experiment with the variables that affect the process.

This paper concerns itself with a laboratory study on the behavior of negative skin friction on model piles. The literature is reviewed, the approach taken is described, and a number of separate aspects of the problem are investigated. These are the fundamental behavior of downdrag, the effect of pile batter, the effect of pile group spacing, the effect of varying the soil-water content, and the effect of different pile materials.

Whenever the magnitude of downdrag force becomes excessively large, the foundation designer is often hard pressed for an alternate scheme. Quite often there is no alternate, so that a method whereby downdrag is significantly reduced, or even eliminated, is desirable. Thus, the use of pile coatings as a preventive measure against downdrag has also been investigated. Asphalt coating viscosity and thickness have been varied and are presented. Generalized conclusions are presented in the summary.

BASIC PROBLEM OF DOWNDRAG IN DEEP FOUNDATIONS

In the design of a deep foundation (e.g., a pile foundation), the ultimate carrying capacity consists of 2 components: the point capacity and the capacity along the shaft.

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This is shown in Figure 1 for both the standard case and the downdrag case. There it is shown that

$$Q_o = Q_p \pm Q_s \qquad (1)$$

$$Q_o = A_p p_o \pm A_s s_o \qquad (2)$$

where

Q_o = ultimate pile capacity,
A_p = area of pile point,
p_o = unit point resistance,
A_s = surface area of pile shaft,
$+s_o$ = positive skin friction,
$-s_o$ = negative skin friction, and
$-Q_s$ = $-A_s s_o$ = downdrag force.

In the downdrag case (Fig. 1b), the problem becomes one of estimating the magnitude and behavior of the term $-s_o$ in Eq. 2. When this value is obtained, the downdrag force, $-A_s s_o$, can be easily obtained. This situation occurs with point-bearing piles where settlements of the pile point are either nonexistent or small.

The physical situations that bring about negative skin friction are well established and are as follows.

1. Remolding of the soil due to pile driving—When piles are driven in clay soils, there is an immediate loss of strength in the soil adjacent to the pile. With time there is a regain in strength (thixotropy) with the possibility of some negative skin friction. This situation probably gives the least amount of downdrag when compared with other situations. An estimate of its magnitude is given by Johnson and Kavanagh (13).
2. Soils undergoing consolidation—Compressible soils that are undergoing active consolidation when the deep foundation is placed will produce downdrag. This consolidation settlement occurs by the usual mechanism of dissipation of excess pore-water pressure but is prevented from occurring adjacent to the pile because of the adhesion and friction of the soil to the pile.
3. Surcharge-loaded soils—This situation occurs when a surcharge load is placed on the ground surface around a previously installed pile in which the foundation soil was in equilibrium or when a lowering of the groundwater table occurs. The surcharge load will cause settlement that is prevented by the previously installed piles, thereby mobilizing negative skin friction. Depending on the magnitude of the surcharge load, and the nature of the compressible soil, this situation is likely to cause the maximum amount of downdrag force on deep foundations.

NEGATIVE SKIN FRICTION COMPUTATIONAL METHODS

There are numerous methods available for predicting the magnitude of negative skin friction or the downdrag force resulting therefrom or both. Many methods assume that negative skin friction is directly analogous to the Mohr-Coulomb failure criterion when expressed as follows:

$$-s_o = c_a + \bar{\sigma}_h \tan \delta \qquad (3)$$

$$-s_o = c_a + K\bar{\sigma}_v \tan \delta \qquad (4)$$

$$-s_o = c_a + K\gamma' z \tan \delta \qquad (5)$$

where

$-s_o$ = negative skin friction,
c_a = adhesion of soil to pile ($0 \le c_a \le \bar{c}$),
$\bar{c}$ = effective cohesion,

$\bar{\sigma}_h$ = average effective horizontal pressure,
$\bar{\sigma}_v$ = average effective vertical pressure,
K = coefficient of earth pressure ($K_A \leq K \leq K_p$),
K_A = coefficient of active earth pressure,
K_p = coefficient of passive earth pressure,
γ' = effective soil unit weight,
z = depth beneath ground surface,
δ = angle of shearing resistance soil to pile ($0 \leq \delta \leq \bar{\phi}$), and
$\bar{\phi}$ = effective angle of shearing resistance of soil.

Table 1 gives a chronological ordering of the various methods and a brief comment concerning each. In the 21 years represented in this table, we have gone full circle from the Terzaghi and Peck (21) suggestion to the Endo et al. (8) solution to the problem. Most investigations utilized Mohr-Coulomb shear strength with major differences in the methods of evaluating c_a, K, and δ. Others feel the problem to be more analogous to consolidation, in that the forces causing consolidation are related to or are equal to the downdrag force.

FULL-SCALE FIELD TESTS

Some of the previous methods for the computation of negative skin friction are based on the experience and intuition of the authors, and others are based on full-scale field tests. As mentioned previously, field testing is much more difficult than standard load transfer problems because of the long measurement periods involved. It is impractical to force consolidation settlements when one is dealing with low permeability soils since the time involved can be decades. Nevertheless, there have been field tests conducted (Table 2) involving different pile lengths, types, soils, and measurement techniques. As admirable as these tests have been, they also bring out the basic difficulty in drawing firm conclusions since so many different variables are involved.

Significant among these tests, however, is the work of Johannessen and Bjerrum (12), who measured negative skin friction on 15-in. diameter pipe piles in a soft to medium-soft marine clay. The negative skin friction was mobilized by 30 ft of surcharge load. This resulted in an average skin friction of 900 tsf in the lower section of the pile and at the pile point a maximum value of 2,000 tsf. Thus, an approximate downdrag force of 250 tons was at the pile point. This resulted in penetration of the pile point into the rock underlying the clay and exceeded the pile's ultimate capacity.

MODEL TESTING FACILITY

Because of the serious nature of the problem and the expense involved in full-scale field testing, a laboratory setup that could simulate the downdrag phenomenon on model piles was constructed. Model tests have been previously conducted by Whitaker (23) on pile groups and by Mazurkiewicz (16) on skin friction in sands. As shown Figure 2, the soil is placed in a 3-ft diameter and 3-ft high tank with a reaction frame on top. The ½-in. thick surcharge load plate has a 1½-in. diameter hole in the center and ¼-in. clearance around the outside. Load is applied to the plate and held constant by means of hydraulic jacks fastened to the reaction frame. Dial gauges are placed on the load plate to ensure uniformity of settlement and to measure surface deflections. The 1-in. diameter model pile is placed through the center hole in the surcharge plate and is fixed to a proving ring and then to the reaction frame. The pile being fixed in position simulates a point-bearing pile in the field. The proving ring records the total downdrag force from which average negative skin friction values can be computed.

The soil used throughout the tests to follow is a slightly organic clayey silt of medium plasticity (OH-OL by Unified Soil Classification System). Its in situ water content is near the liquid limit of 55 percent. The plasticity index is 20 percent, and the shrinkage limit is 27 percent. The particle size distribution curve is shown in Figure 3. All tests were conducted with the soil near its in situ water content except for the sequence that evaluated the effects of varying water content.

Figure 1. Basic phenomenon involved.

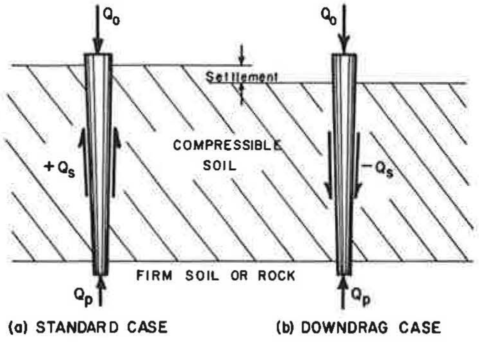
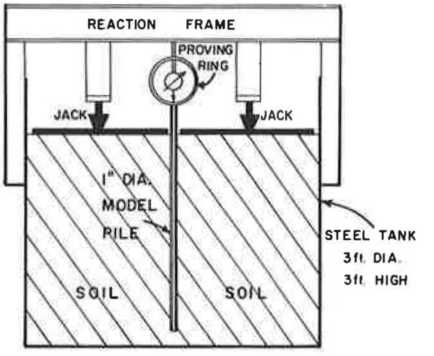


Figure 2. Experimental setup.



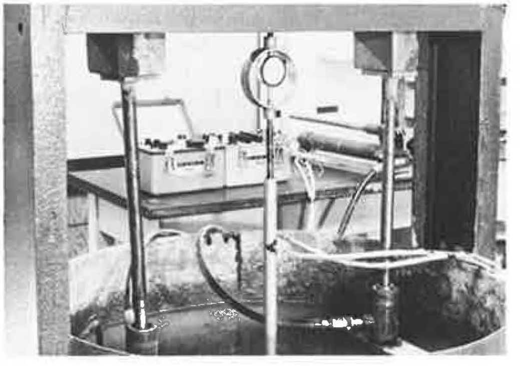


Figure 3. Particle size distribution of soil.

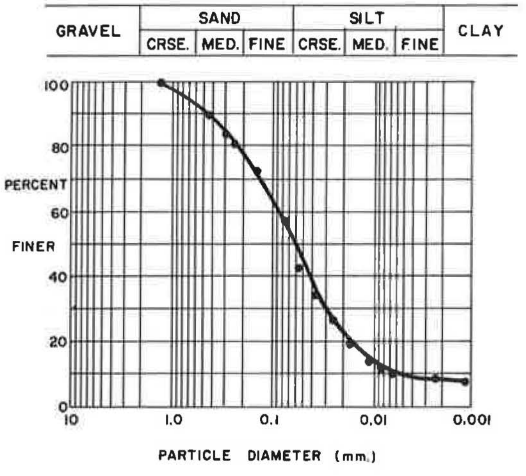


Table 1. Methods for computing negative skin friction.

Author	Reference	Year	Comment
Terzaghi and Peck	21	1948	$0 \leq -s_o \leq \tau$
Moore	17	1949	$-s_o = (\pi\tau + \bar{\sigma}_v) \tan \delta$
Zeevaert	24	1959	Analytic expression utilizing K_o
Buisson, Ahu, and Habib	5	1960	Analytic/graphic procedure requiring soil and pile characteristics
Elmasry	7	1963	Empirical equation based on statistical theory (15)
Weele	22	1964	Similar to tension piles
Johannessen and Bjerrum	12	1965	$-s_o = 0.20\ \bar{\sigma}_v$
Johnson and Kavanagh	13	1968	Analogous to solution of consolidation problem
Bowles	2	1968	$K_A \leq K \leq K_p$
Hansen	11	1968	Analytic expressions predicting upper limits
Poulos and Mattes	20	1969	c_a, K_o, δ from Broms (4)
Endo et al.	8	1969	$-s_o = \tau$ where τ is obtained from an unconfined compression test

Table 2. Full-scale downdrag tests.

Author	Reference	Year	Pile Length (ft)	Pile Material	Soil	Measurement Method
Weele	22	1964	45	Timber	Soft clay	Extensometer
Locher	15	1965	40	Concrete	Soft clayey silt	Extensometer
Johannessen and Bjerrum	12	1965	140	Steel pipe	Soft to medium-soft marine clay	Extensometer
Bozozuk and Labrecque	3	1968	270	Composite	Marine clay	Strain gauges
Bjerrum, Johannessen, and Eide	1	1969	100 to 190	Steel pipe	Marine clays	Extensometer
Endo et al.	8	1969	100 to 140	Steel pipe	Soft alluvial silt	Technique varied
Fellenius and Broms	9	1969	225	Concrete	Normally consolidated clay	Strain gauges

MODEL TESTING RESULTS

Negative Skin Friction Behavior

To verify the experimental setup just described and to obtain a better understanding of negative skin friction behavior require the downdrag distribution along the pile's length. The following technique was developed for this purpose (14).

A 1-in. OD by 7/8-in. ID steel pipe was split along its axis and instrumented with 10 strain gauges (5 on each half) at 5-in. spaces. The strain gauge leads were brought up in the center of the pipe and out through its sides above the soil surface and then attached to standard instrumentation equipment. The pile halves were joined by a waterproof epoxy cement. The bottom of the pile was sealed and the top fixed to a proving ring as previously described.

The results of this phase of the study are shown in Figure 4. At low surcharge, hence low surface deflection, the entire downdrag force is carried in the upper portion of the pile. As surcharge increases, this force descends deeper along the pile until it reaches the bottom. Still further increase in surcharge load causes the slope of the force distribution to decrease until the ultimate negative skin friction value is reached. This behavior appears to be reasonable, and its total force agreed with the proving ring affixed to the top of the pile. In the remaining tests only the proving ring was used for measurements. However, for longer piles than those used here, the location of a neutral point (8), where the skin friction goes from negative to positive, becomes significant and must be determined in this manner.

Effect of Pile Batter

For anticipated horizontal loads and for greater stability, piles are often driven off vertically, i.e., batter piles. The amount of batter varies considerably, and the effect of negative skin friction on such piles is of interest. The experimental setup easily accommodated the inserting of piles on an angle to simulate this condition. To have a valid comparison, we tested 3 steel piles simultaneously, the center one always being vertical, and the valves compared well with the previously obtained values. The time between load increments was varied and found to have negligible effect on the maximum value of negative skin friction. There was approximately a 1-week interval between tests so that equilibrium could be established after the piles were inserted.

Figure 5 shows the study of this sequence of tests. Clearly, an increase in the amount of batter increases the average negative skin friction. The apparent reason is that one has not only the adhesion of the soil to the pile, which is independent of positioning, but also a direct contribution of the pressure from the soil above. As batter increases, this vertical pressure also increases in the proportion as shown. This response is contrary to the only known comparison made in the field. Endo et al. (8) have compared a vertical pile to one placed at a 1:7 batter, and the result was a 16 percent reduction in negative skin friction in the case of the battered pile. No discussion as to the reason for this response was offered.

Effect of Pile Group Spacing

Since piles are usually placed in a group configuration, a study of the effect of pile group spacing was undertaken. Nine concrete piles were placed in a 3 by 3 group and fixed to a single steel plate at their tops. This, in turn, was fixed to a single proving ring as shown in Figure 6. The spacing to diameter (S/D) ratio was varied at 1.0, 1.5, 2.0, 3.0, and 5.0. Individual holes for each of the piles were cut in the surcharge plate for each different spacing, and testing proceeded as before.

The results shown in Figure 7 are for average negative skin friction at maximum, 1/2 maximum, and 1/4 maximum surface deflections. A distinct break in the curves at about S/D = 2.5 is noted. For smaller S/D ratios, the negative skin friction values rapidly decrease. This is completely analogous to positive skin friction studies (23) in that a block failure will occur only at very close S/D ratios. The purpose of presenting 3 curves is to show that this trend is consistent over the entire range of average negative skin friction values and does not occur only at the limiting value. This value of S/D =

Figure 4. Distribution of downdrag force.

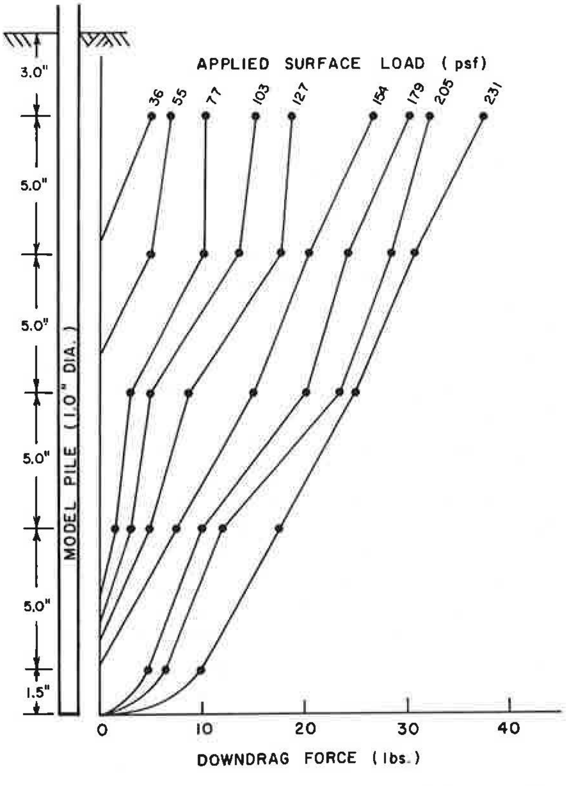


Figure 5. Effect of pile batter on average negative skin friction.

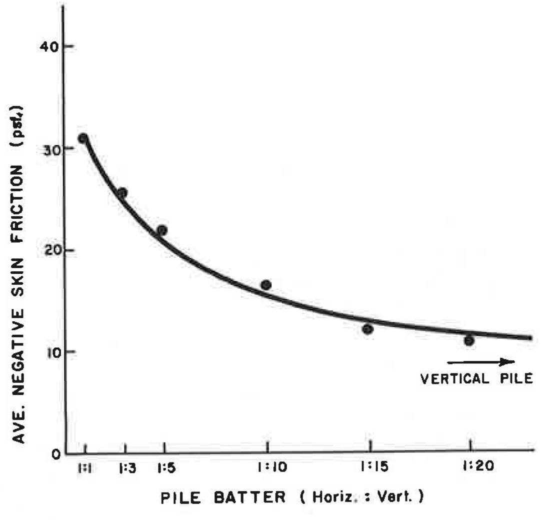


Figure 6. Experimental setup for group testing.

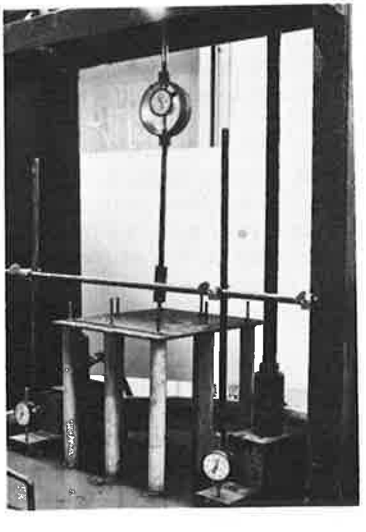
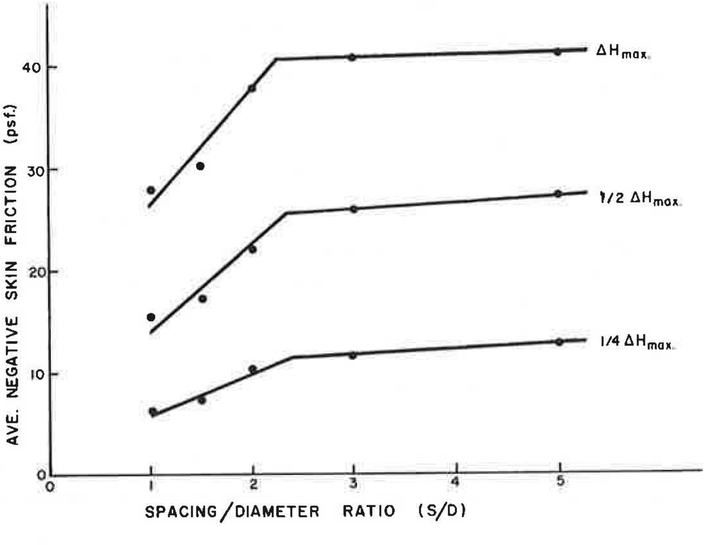


Figure 7. Effect of pile group spacing on average negative skin friction.



2.5 was suggested by Terzaghi and Peck (21) as being the recommended pile group spacing that is practical and yet minimizes negative skin friction.

Effect of Water Content and Pile Material

Piles made of the 3 common pile-forming materials (wood, concrete, and steel) were installed and tested simultaneously. Each was attached to a separate proving ring as shown in Figure 8. After this sequence of tests the assembly was dismantled and the soil was removed, dried, and replaced in the tank at a lower water content. This sequence was continued until the water content was below the shrinkage limit.

The combined results of the effect of water content and the effect of pile material is shown in Figure 9. Superimposed on this curve (dashed line) is the shear strength of the soil as determined from the unconsolidated-undrained triaxial tests below the plastic limit and from the laboratory vane shear tests for the soils above the plastic limit. All pile materials show increased average negative skin friction with decreasing water content. This is as expected since the shear strength of the soil is also increasing with decreasing water content. Of concern, however, is the relative positioning of the curves of different pile materials. At the liquid limit the wood pile develops full shear strength, the concrete pile develops 50 percent of the shear strength, and the steel pile develops 40 percent of the shear strength. This agrees reasonably with the published values of adhesion by Potondyi (19). At lower water content the steel pile maintains an approximate relation with strength, but the concrete and wood piles develop a much lower proportion of the total available shear strength. The tests were repeated several times at varying load rates and time intervals between tests with the same outcome for each sequence. The reason for this behavior is not clearly understood. It is possible that the soil, being below the shrinkage limit, may not have been completely bonded to the pile surface. Thus computation of average negative skin friction based on the total surface area of the pile may have resulted in values that are too low.

Effect of Asphalt Viscosity

The physical situations where negative skin friction is likely to occur have been previously described. If there is no other foundation scheme available to the designer, it may be proper to partially eliminate downdrag from occurring. The logical technique is to coat the pile's surface with a material that will not allow load transfer to pass onto the pile. Because of the large quantities involved and the cost thereof, the use of asphalt coatings seems reasonable and has been used in the field (10). Asphalts of different viscosities were tested, wherein the viscosity was indicated by its penetration grade and varied from very soft (600 to 800 penetration) to very stiff (60 to 70 penetration). The piles were coated with a $\frac{1}{8}$-in. thick layer of asphalt in this sequence of tests.

The results are shown in Figure 10 for the 5 asphalts tested. Most significant in such tests is the rate of surcharge load application. The slower load is applied, the lower is the developed average negative skin friction. Load increment time was extended until the curves became approximately constant. This load rate appears to be related to the coefficient of consolidation of the soil, c_v. As anticipated, the stiffer the asphalt is, the higher the average negative skin friction is. All curves represent a significant reduction in average negative skin friction from the untreated piles that were previously tested.

Effect of Asphalt Thickness

The previous set of tests utilized different viscosity asphalts but all were coated on the piles in $\frac{1}{8}$-in. thickness. This series varies the thickness from $\frac{1}{16}$ to $\frac{1}{4}$ in. These thickness tests were performed on the stiffest asphalt (60 to 70 penetration), the medium asphalt (150 to 200 penetration), and the softest asphalt (600 to 800 penetration).

The results are shown in Figure 11, which is plotted similar to Figure 10. The medium viscosity asphalt curves are shown as dashed lines. All curves show decreasing negative skin friction with increasing load time increments. Average negative skin friction decreases with increasing asphalt thickness. This is as anticipated since the

Figure 8. Experimental setup for pile material study.

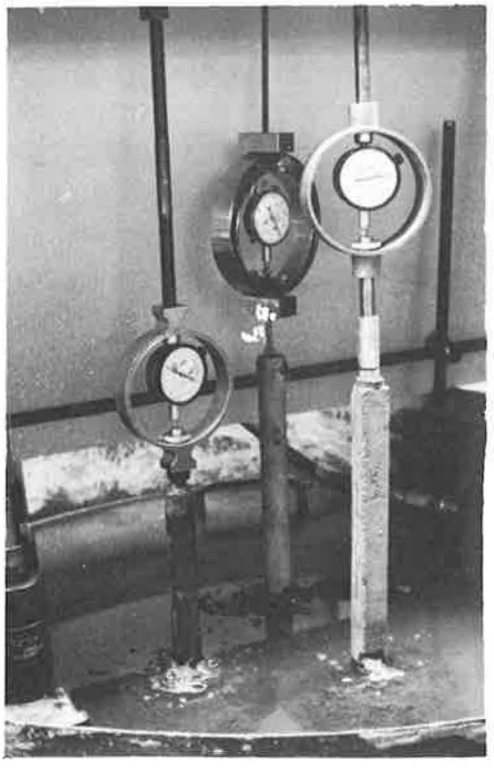


Figure 9. Effect of water content and pile material on average negative skin friction.

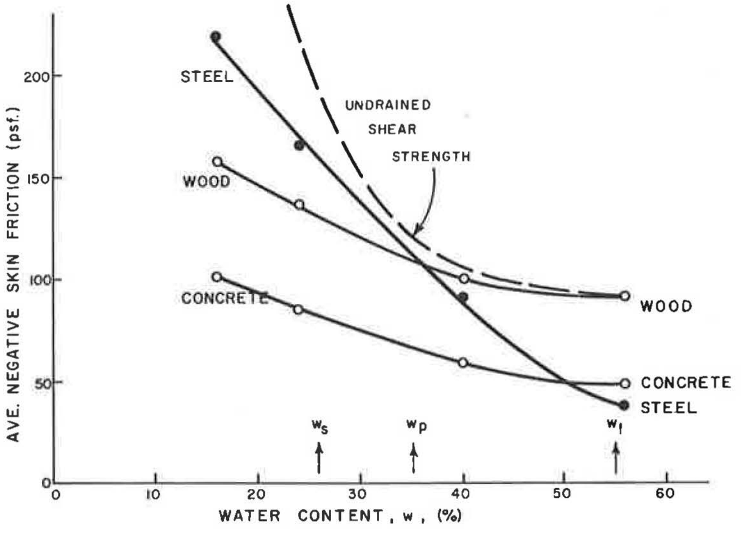


Figure 10. Effect of viscosity of asphalt coating on average negative skin friction.

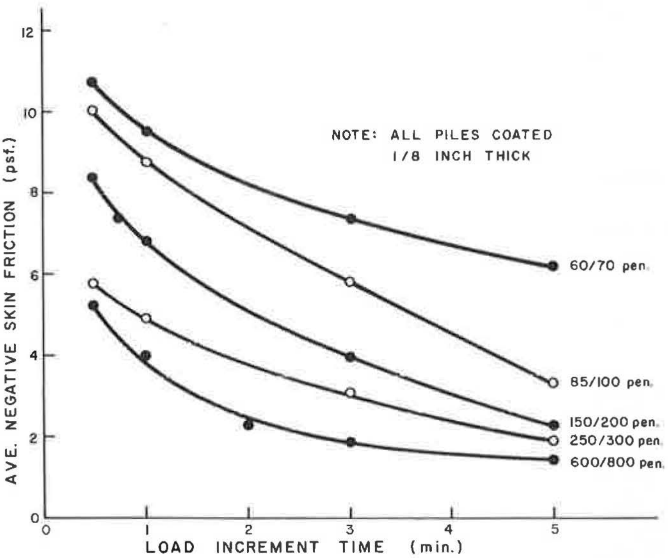
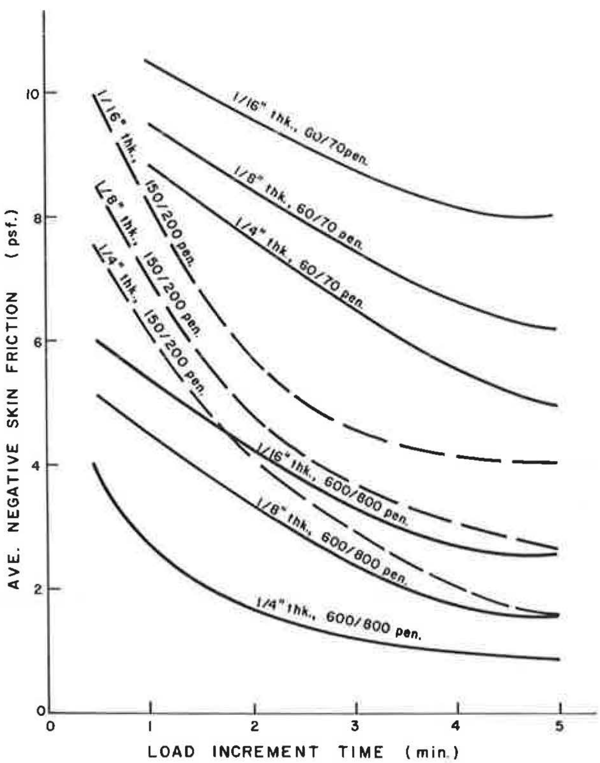


Figure 11. Effect of thickness of asphalt coating on average negative skin friction.



load transfer through the asphalt cannot be achieved with a thicker layer; thus, the asphalt absorbs a larger proportionate amount of the soil displacement and less is transferred onto the pile.

SUMMARY

Although the exact technique of computing downdrag force in a generalized form is still not available, a number of aspects of its behavior have been investigated. Some definite conclusions can be drawn therefrom.

1. As surface deformation proceeds, negative skin friction effects are felt on the pile at its top and proceed down from the pile to the bottom. Continued soil deformation causes equal increments of negative skin friction to be absorbed by the pile until the maximum value is mobilized over the entire length of the pile.
2. Batter piles develop larger downdrag forces than vertical piles. For pile batters greater than 1:10, average negative skin friction increases rapidly. These model test results are in disagreement with the only known field test on the effect of batter on negative skin friction.
3. Pile group spacings should be kept as low as possible to minimize negative skin friction. However, only with spacing-diameter ratios less than 2.5 is a significant reduction in average negative skin friction noticed, and such close spacings are often not practical.
4. As the water content of the soil decreases, the average negative skin friction increases. Since the shear strength of the soil is also increasing, there may be some relation available.
5. Tests on the effects of pile material on negative skin friction are not conclusive. This finding may indicate that the adoption of Mohr-Coulomb failure criterion to the prediction of negative skin friction will be difficult.
6. Use of asphalt coatings on deep foundations to reduce negative skin friction shows definite promise. It has been shown that the softer and thicker the asphalt coating is, the lower is the negative skin friction that is transferred to the pile.

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