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EFFECT OF CONSTRUCTION PROCEDURE ON LOAD-CARRYING BEHAVIOR OF SINGLE PILES AND PIERS

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ABSTRACT

From measurements taken at four sites, it became possible to compare the performance of five types of foundations: Benoto concrete piles, precast concrete driven piles, piles bored and cast with the use of casing, piles bored and cast with the use of bentonite and excavated concrete piers, lined with concrete blocks. Steel rods, freely supported within the piles, enabled settlement readings at various depths for all loading stages. Deformations were found, from which the load distribution along the piles was computed. By this method the total applied load was separated into friction and end-bearing.

In all cases reported, the performance of piles and piers was dominated by their ability to mobilize friction.

INTRODUCTION

Experience has shown that, in many cases, a piled foundation may have both technical and economical advantages over shallow footings. These advantages become more apparent when high working-stresses (up to 70 kg/cm^2) are utilized. As the procedures for pile construction vary widely, the choice of the method best suited for each case must be based on economic considerations, as well as on the load-carrying properties of each type. This work deals with piles of four different types and one kind of pier, constructed on four projects for which the Authors served as foundation consultants. At three sites, the piles were test-loaded as part of the sub-surface investigation program for the planned structures. At the fourth site, settlements of the actual structure were measured during construction. This work deals with the test results, which enabled a comparison between the various methods.

DESCRIPTION OF PROJECTS AND TESTS

The four projects at which the observations were made are as follows:

(1) The Post and Parcel Building at Yad Eliahu, Tel-Aviv (Site Y.E.)

The main structure will be up to 70 meters high, and foundations loads up to 2,500 tons. The soil profile is represented in Fig. 1(a).

Two kinds of piles were tested at this site: Benoto piles, 67 cm in diameter and 8 m long, and driven piles of precast, prestressed concrete, 35 cm square and 7 m long. All were constructed after the upper 6 m have been excavated.

(2) The New Hospital at Tel Hashomer (Site T.H.)

The new hospital at Tel-Hashomer will include a twelve-story central building, where the loads on the foundations will be between 400 and 1,700 tons. The soil profile is seen in Fig. 1(b).

The piles tested were all cast in situ, 65 cm in diameter and 12 to 15 m long. Some of the piles (nos. 201-204) were first bored and then cased, while the rest (nos.205-207) were bored using bentonite slurry. All casings were extracted during the concreting of the piles.

(3) The New Hospital at Hadera (Site HD.)

The main building will have 6 to 8 stories, with design loads on the foundations of up to 900 tons. The soil profile is shown in Fig. 1(c).

The foundations tested at this site were bored piles, cast in situ with bentonite slurry. The piles were 65 cm in diameter and 26 m long.

(4) Sharon Hotel-Herzlia (Site S.H.)

The new Sharon Hotel in Herzlia has 13 stories above ground, with loads of about 6,000 tons from the central core and 1,000 tons on each of the columns at the four corners of the building. The soil profile is represented in Fig. 1(d).

The building was constructed on excavated piers, lined with concrete blocks. The depth of the piers was about 18 m, with diameters varying between 130 and 150 cm.

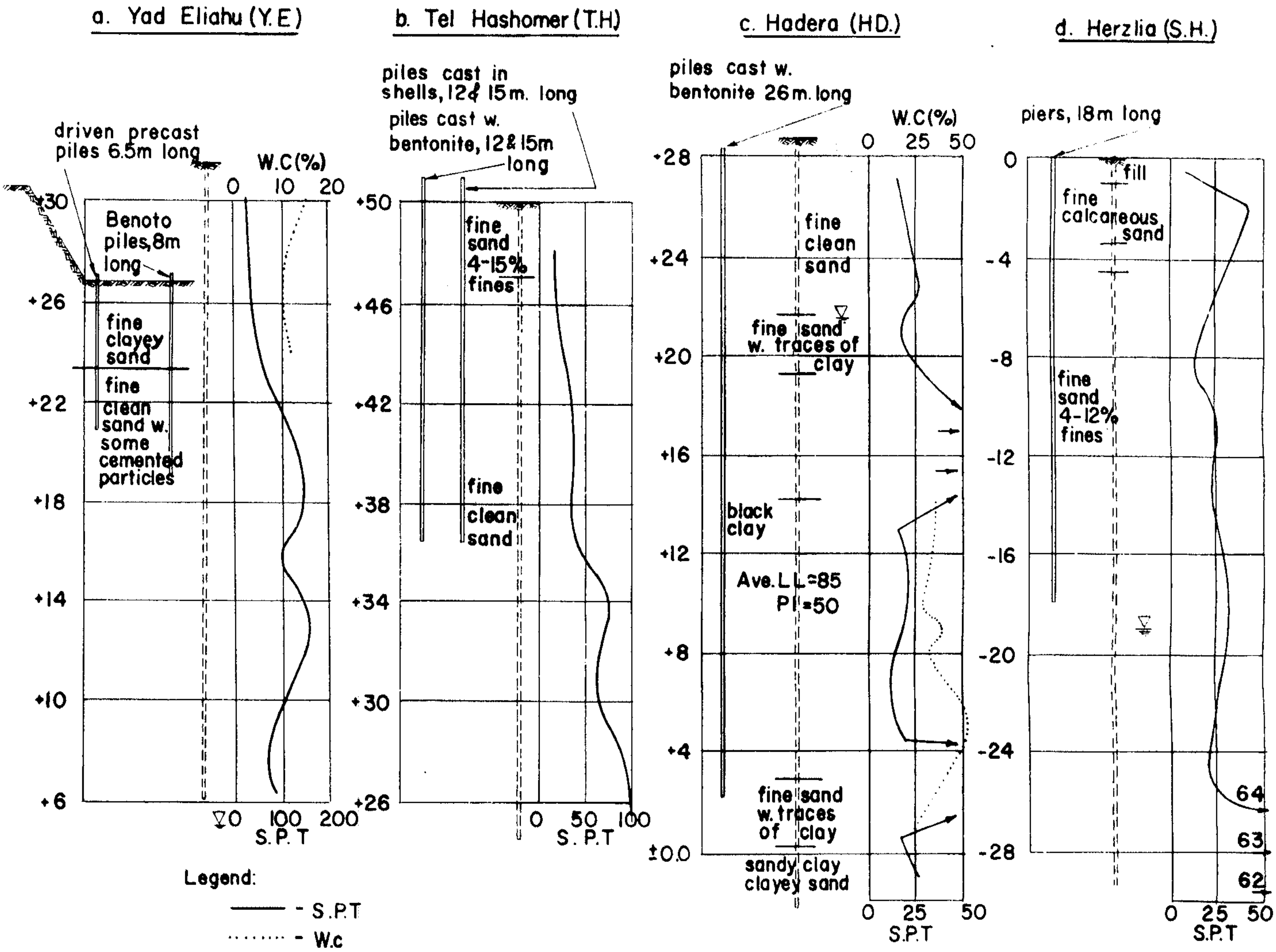

FIG. 1. Soil Profiles and Pile Types.

LOAD TESTING PROCEDURE

At each site two or more piles of the type to be tested were driven or cast in place, and then tested, not less than a month after casting or driving. Load tests were performed according to the method proposed by ASTM (1964), and load was applied to piles by hydraulic jacks against a weighted platform. Settlements within the pile were measured by a method similar to that proposed by HANSEN and KNEAS (1942). This consisted of hollow tubes, with freely-supported rods inside each.

SEPARATION OF PILE LOAD INTO FRICTION AND END-BEARING (GRAPHICAL METHOD)

Let the force in the section A of the pile, at a depth Z from the surface, be denoted by P (Fig. 2). Under this force, an infinitesimal element dZ is shortened by dε. According to Hooke's law:

$$d\varepsilon = \frac{P}{A\,E_c}\,dZ \qquad \ldots (1)$$

where E_c is the Young's Modulus of the pile material.

The deformation of the pile length from A to B is, therefore:

$$\varepsilon = \frac{1}{A\,E_c}\int_{Z_A}^{Z_B} P\,dZ \qquad \ldots (2)$$

The integral is equal to the area under the curve $P(Z)$ between A and B. When divided by the length l_n of this part of the pile, it gives the mean force in this part:

$$P_2 = \frac{\int_{Z_A}^{Z_B} P\,dZ}{l_n} = \frac{A\,E_c}{l_n} \qquad \ldots (3)$$

This operation is carried out for each part of the pile under any load P_o. The results are then drawn to some convenient scale, in the form of three descending steps. At this stage, a curve may be drawn, according to the following rules:

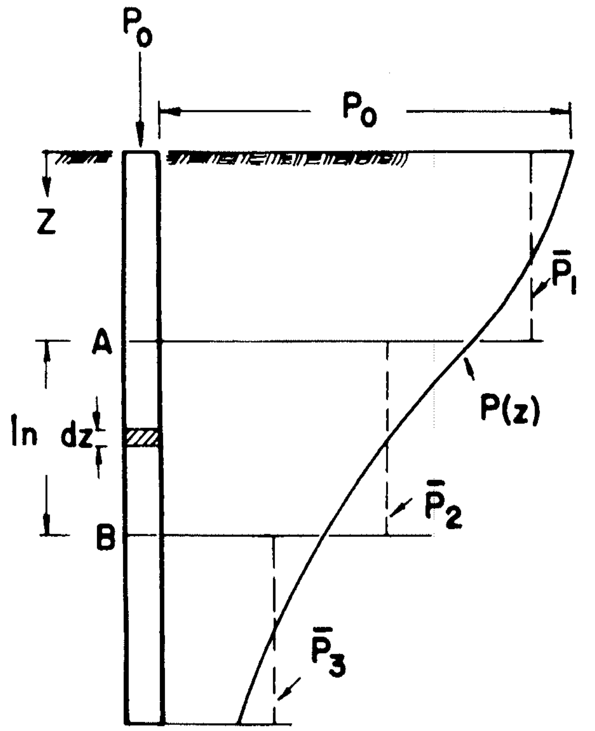

FIG. 2. Computation of Force Distribution Along the Pile.

(a) At ground level the force P is equal to the pile load P_o.

(b) The force diminishes with depth. It may remain constant for any length, but it cannot become larger.

(c) In any part, the curve crosses the mean force step, enclosing equal areas on both sides.

(d) The curve should be continuous, with no "jumps". If the soil in which the pile is embedded is fairly homogeneous, the curves should also be smooth.

Theoretically, the number of curves conforming to these conditions is infinite, but experience has proved that the possible range is small, so that fairly accurate results may be expected.

TEST RESULTS — LOAD CAPACITY AND SETTLEMENTS

There are no generally accepted standards for failure based on graphical load vs. settlements representations. Therefore, the pile load tests were analyzed relatively, by comparing the settlements at different butt stress levels. This was done with due regard to the load which caused large settlements, or the "failure load" proposed by TERZAGHI et al (1942): this is the load at which the penetration of the test pile is equal to 10% of the pile diameter.

Table 1. Results of Load Tests

Site	Pile No. and Type	Embedded Length	Maximum Load Appiled	Settlement of Butt at Max. Load	Settlement of Butt after Rebound	Settlement of Tip Max. Load	Settlement of Tip after Rebound	Failure* Load
		cm	ton	cm	cm	cm	cm	ton
Y.E.	102 Benoto	8.1	300	0.6	0.3	0.45	0.30	>300
	103 Benoto	8.1	370	1.8	1.2	1.58	1.20	>370
	104 Benoto Friction	7.7	300	2.5	2.1	2.36	2.12	>300
	105 Driven	6.4	270	4.0	3.1	3.70	3.15	255
	106 Driven	6.4	270	6.5	5.3	6.05	5.20	230
	109 Driven Friction	6.6	230	3.1	2.3	2.90	2.38	230
T.H.	201 Cased	11.9	285	7.7	7.2	7.50	7.10	270
	203 Cased	14.9	255	6.2	5.6	5.75	5.50	255
	204 Cased Friction	14.9	220	6.3	5.8	6.10	5.85	220
	205 Bentonite	11.9	405	2.4	1.9	2.10	1.88	>405
	207 Bentonite	14.8	415	1.1	0.7	0.83	0.67	>415
HD	301 Bentonite	25.3	415	0.5	0.08	0.03	(–) 0.02**	>415
	303 Bentonite	25.2	410	0.5	0.08	0.03	(–) 0.01**	>410

* As defined by Terzaghi et al. : Load at which the penetration of the test pile is equal to 10% of the pile diameter.
**(–) upward movement.

Table 1 shows general data received from load tests, under ultimate loads (as defined by Terzaghi) and after the last cycle of loading.

At Y.E. site, none of the three Benoto piles tested did fail by the above mentioned criterion. Stresses on top of the piles reached 85 to 105 kg/cm^2, with settlements less than 2 cm; even the butt of the "pure friction" pile settled only 2.5 cm (Fig. 3). The three driven piles failed or almost failed under the maximum available load, when the butt stresses reached more than 200 kg/cm^2. At stresses of 105 kg/cm^2, which are similar to the maximum final stress applied on the Benoto piles, the settlements measured only 0.6 to 1.0 cm.

At T.H. site, all three cased piles tested failed when stresses on the butt reached 68 to 82 kg/cm^2. A three meter difference in the lengths of the tested piles did not make any difference in the settlements observed. The two piles stabilized with bentonite, on the other hand, performed much better, and at butt stresses of up to 125 kg/cm^2 none failed. Even at such high stresses, the settlements were only 1.1 to 2.4 cm. Under all loads, the longer pile showed consequently smaller settlements, mostly half of the settlements of the shorter pile.

At the H.D. site only piles stabilized with bentonite were used. These piles settled only 0.5 cm at butt stresses of up to 125 kg/cm^2, and rebounded almost completely.

The piers at S.H., settled between 3.2 and 4.5 cm under loads of 520-570 ton. At this load, the butt stresses were about 36 kg/cm^2.

LOAD TRANSFER

Using the graphical method previously explained, a load separation curve was drawn for each pile tested. In Fig. 4 the skin friction and end-bearing are shown for 100, 200 and 300 ton loads applied to the butt of typical piles.

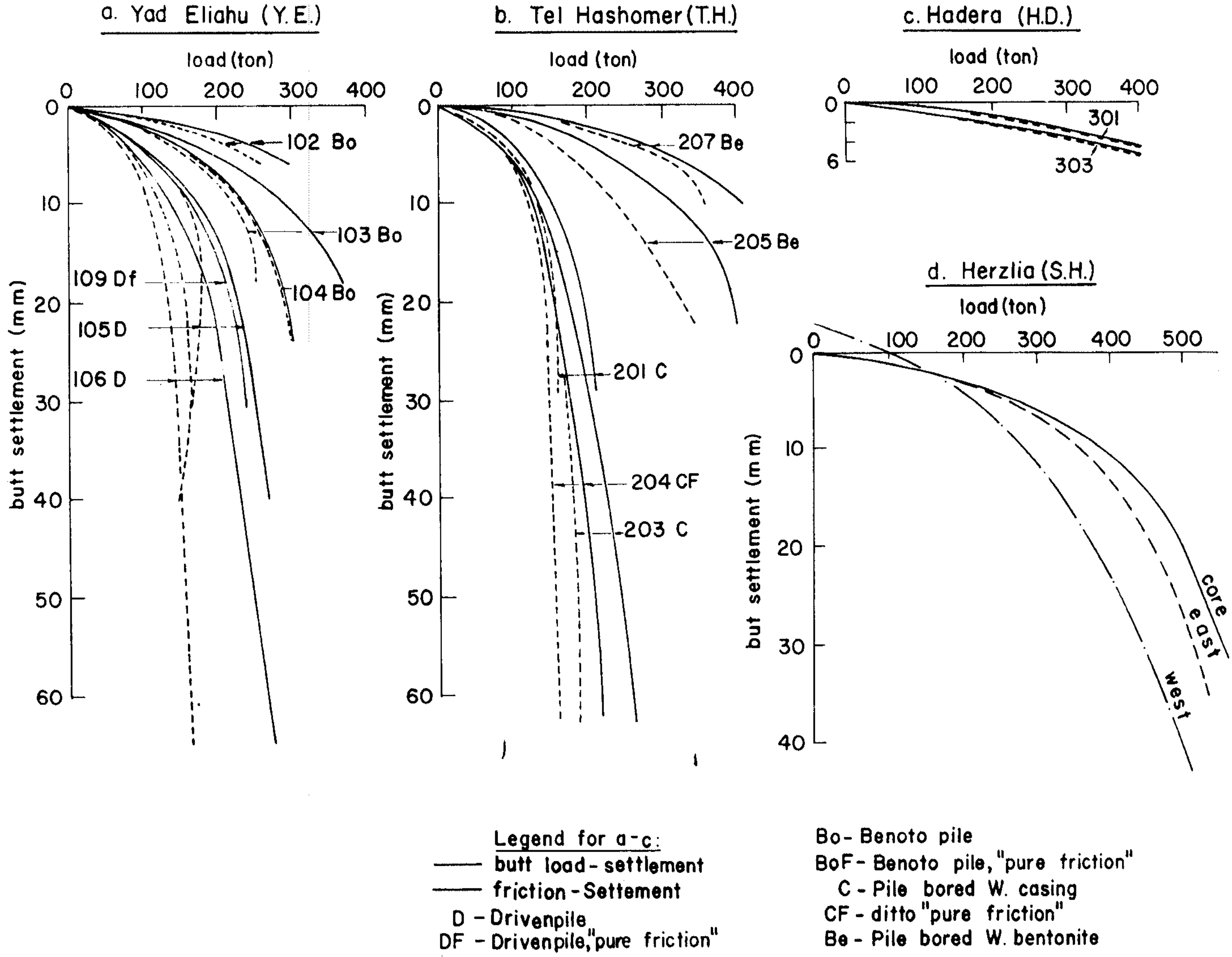

FIG. 3. Load-Settlement and Friction-Settlement of Piles and Piers.

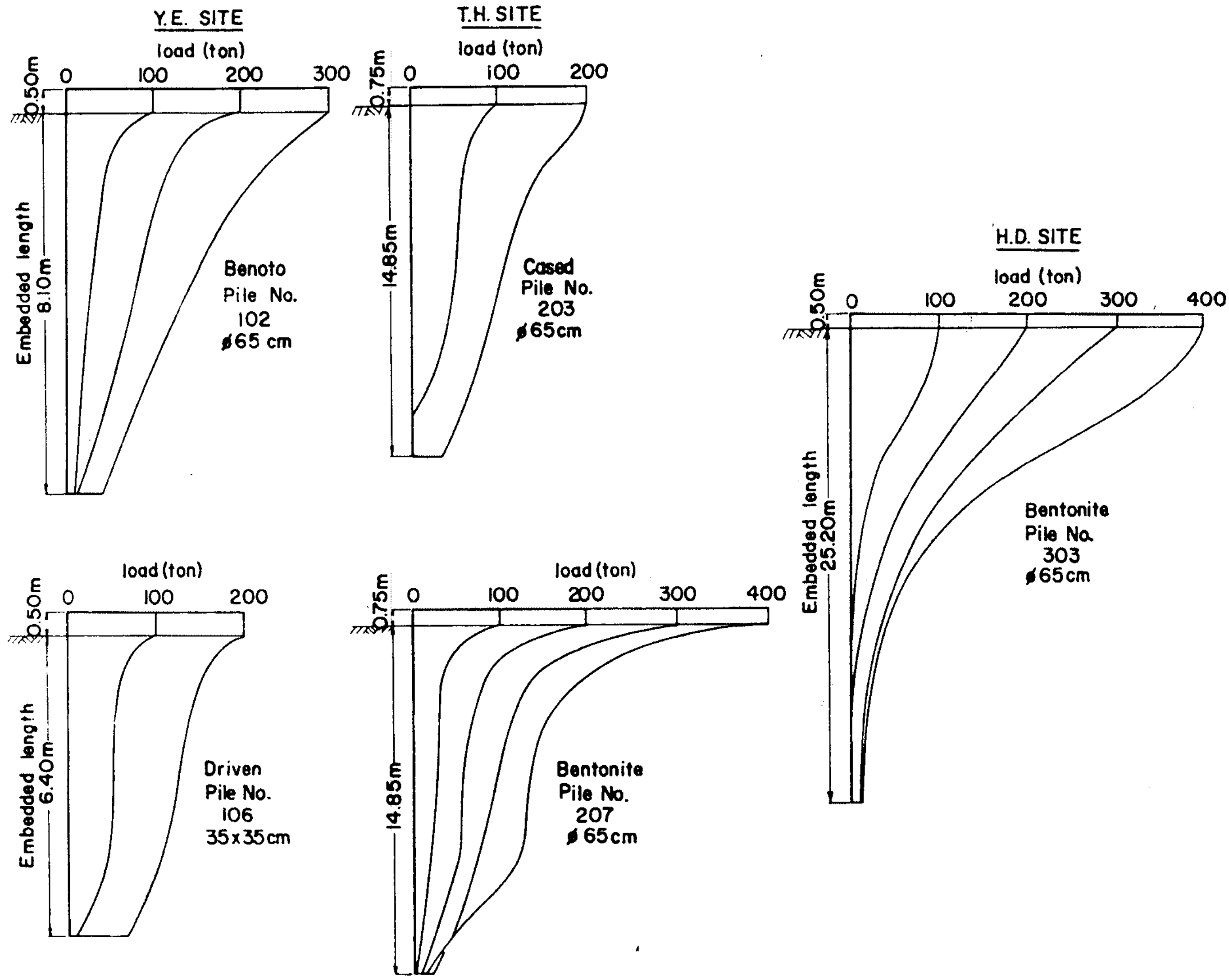

FIG. 4. Distribution of Load Along Piles.

No qualitative difference can be seen between the shape of the curves of the various types of piles, and they all resemble those obtained by THURMAN and D'APPOLONIA (1965) and VESIC (1970). However, the piles differ in the relative magnitudes of skin friction and bearing loads transferred by their tips. Due to the variation in the soils encountered at the various sites (types of soil, relative densities, ground water table) this unequal performance was expected but it became clear that the uneven load transfer was much more affected by the method of construction.

All piles (with the exception of the piers at S.H.) transferred most of the load by friction along their shafts. The driven piles which had the skin friction partially destroyed by jetting, transferred to the tip only 40 to 45% of the total load. Also, this percentage of bearing was reached after settlements of 4 to 6 cm. The rest of the piles developed little reaction at their tips, with the exception of pile B 103 which at final load transferred 32% of it by bearing.. This pile also showed a progressive reliance on point bearing with slight decrease in skin friction. Pile D 105 performed somewhat similarly, while the skin friction dropped remarkably at large settlements.

Values of unit skin friction f_s, for butt settlements of up to 1.0 cm are shown in Fig. 5. The skin friction at these settlements has a special importance, because they are typical for usual working loads.

With the exception of the cased ones, all piles developed unit skin friction values within a relatively close range. The unit skin friction of the Benoto piles was about 20% less than the one of the driven piles, with the exception of pile B 102 which developed a slightty larger friction. The cased piles developed only 20 to 25% of the skin friction of the driven piles, although within a close range.

In this representation of the test results many factors such as the relative stiffness of piles - soils, slenderness ratios etc., were disregarded. These, however, showed little bearing on the performance of the piles tested as

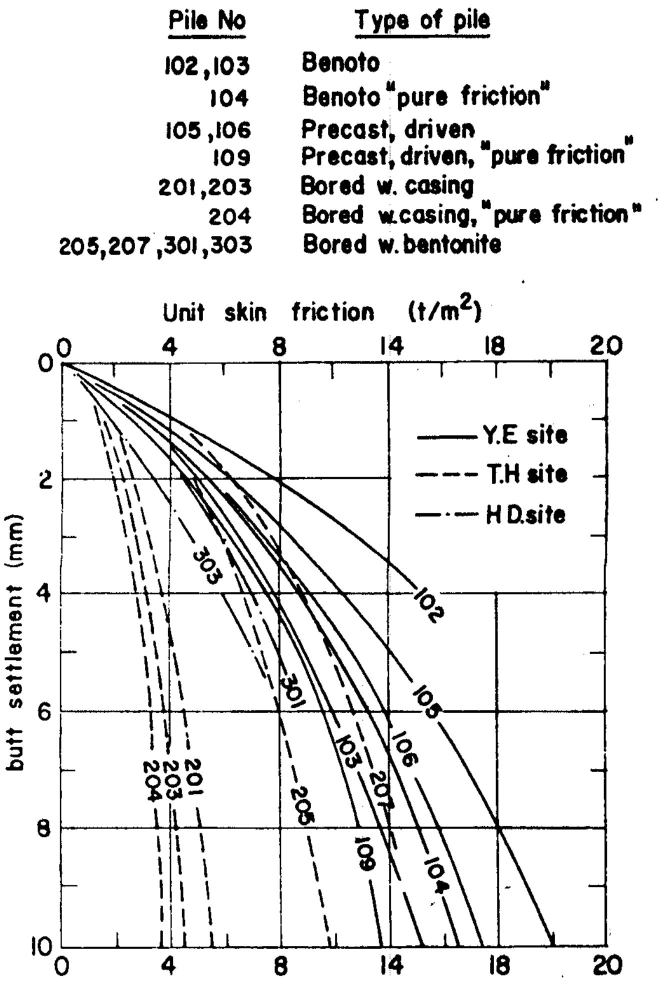

FIG. 5. Unit Skin Friction for Settlements of up to 1 cm.

compared to the effect of the method of installation of these piles.

CONCLUSIONS

It was proved that the method of construction is a major factor in the total behaviour of deep foundation. In some cases, it may be of greater importance than the soil profile.

In the range of depths and diameters reported, both bearing capacity and load settlement behaviour were governed by the ability of the shaft to transfer the load to the surrounding soil by friction. The contribution of end-bearing to the total load-carrying capacity was at all loads only minor or negligible.

All Benoto and driven piles which were jetted settled little under large stresses. Both developed high unit friction along their shafts, with the driven piles having a slight advantage over the Benoto piles.

Cased piles showed a remarkably poor performance while mobilizing only about half of the friction developed by the bentonite piles, at the same soil conditions.

Excavated piers lined with concrete blocks underwent large settlements at moderate stresses. It is believed that this is due to the smaller contribution of the shaft in transferring the friction.

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