Investigation of Pile Resistance by Combined Sounding

Etude de la résistance des pieux par sondage combiné

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SUMMARY

This report contains a description of experimental work carried out by the Scientific Research Institute of Foundations and Underground Structures at several sites and involving the investigation of the resistance of reinforced concrete piles by means of the combined sounding method. The principal assumptions used as the basis of this method are explained and briefly described. The results of the determination of the resistance of reinforced concrete piles by the method of combined sounding and a comparison of these results with those obtained by testing the same piles with static loads is presented, and formulae for calculating the resistance of piles by the method of combined sounding are given.

Field and laboratory tests have confirmed the initial assumptions that the specific resistances of the lower end and the side surface of piles that are subject to vertical loads depend mainly upon the properties of the soil surrounding the individual pile and not on the dimensions of its cross-section. The results of these investigations permit the use of combined sounding for determining the resistance of piles, instead of labour-consuming and expensive pile load tests.

SOMMAIRE

L'exposé comporte une description des travaux expérimentaux pour l'étude de la résistance des pieux en béton armé par la méthode du sondage combiné effectué sur le chantier par le Centre de Recherches sur les Fondations et les Constructions Souterraines. Les suppositions principales de cette méthode sont expliquées et brièvement décrites. Les résultats de la détermination de la résistance des pieux en béton armé, par la méthode du sondage combiné, sont comparés à ceux obtenus pour les mêmes pieux à l'aide de charges d'essai statiques. Enfin on donne les formules de calcul de la résistance des pieux par la méthode du sondage combiné.

Les expériences effectuées sur le chantier et au laboratoire ont confirmé la supposition que la résistance de l'extrémité inférieure et de la surface latérale des pieux subissant l'action des charges verticales dépendent essentiellement des propriétés du terrain entourant le pieu et non pas des dimensions de la section transversale du pieu. Les résultats de ces recherches permettent l'emploi du sondage combiné pour déterminer la résistance des pieux au lieu des essais de charge qui coûtent cher et prennent beaucoup de temps à effectuer.

THE DETERMINATION OF THE BEARING CAPACITY of piles is a very pressing problem, as the existing theoretical and empirical methods of calculation do not make accurate determination of their resistance possible. The most reliable method, i.e. the testing of piles under a trial load, is employed only when performing work involving the installation of pile foundations, but cannot be used during the surveying and design stage, as the design and surveying organizations do not possess any equipment for driving piles. In any case this method is very laborious, requiring considerable manpower, equipment, and time, and is therefore used only in exceptional cases. Piles, as a rule, were used in soils that do not have sufficient strength, whereas at present in the Soviet Union when erecting residential and public buildings pile foundations are used to a considerable extent in various soils, except in rock, half-rock, and coarse gravel.

For this reason the development of a rapid, inexpensive, easy and reliable method of determining the resistance of piles has become an urgent problem. The sounding method, which is widely used in many countries for investigating the construction properties of soils (strength, density, modulus of deformation), as well as the depth of driving and the bearing capacity of the piles, is the most suitable method for this purpose.

To determine the resistance of piles to vertical forces the most reliable method is the testing of probes driven into the soil under a static load applied in stages, similar to the testing of test piles, and the determination of the static specific resistances of the lower end (cross-section) and the side surface of the probes. This method, which we have named "combined sounding," is based on the specific resistance of the lower end and of the side surface of the piles which depends mainly on the properties of the soil surrounding the pile, and not upon its cross-section.

The method of penetration by continuous driving of the probe into the soil, which is used in many countries for determining the bearing capacity of piles, cannot be considered entirely satisfactory as it only permits the determination of an estimated load on the pile.

Most investigators (Haefeli, de Beer, van der Veen, and others) propose the determination of the estimated safe load from the formula:

$$P_{cb} = 1/K_b \cdot \sigma_b F_{cb} \tag{1}$$

where σ_b is the specific resistance to penetration of the probe cone in kg/sq.cm.; F_{cb}, cross-section area of pile (sq.cm.); and K_b, the safety factor 2.5 to 3.9.

In 1932 Tsytovitch came to the conclusion that the settlement of piles subject to vertical loads depends upon the density and the consistency of the soil located under the lower end and around the body of the pile. Terzaghi (1932), in investigating the resistance of driven piles to a vertical load, and employing Lame's solution to determine the stressed state of the consolidated soil envelope, proved that the magnitude of the specific resistance acting on the surface of the piles does not depend upon its diameter.

Preliminary investigations carried out in the Institute of Foundation Beds, and aimed at determining the construction properties of soils and the bearing capacity of piles by sounding, disclosed that the specific resistances on the side surface of rod probes with diameters of 50 mm practically coincide with the specific resistances on the side surface of reinforced concrete piles (Shashkov, 1960). To check this proposition under laboratory conditions experiments were carried out with rod probes having diameters of 27.62 and 89 mm, respectively driven in pairs into sand to a depth of 1.10 to 1.20 meters and tested under a static load (Table I).

TABLE I. COMPARISON OF SPECIFIC STATICAL RESISTANCES ON SIDE SURFACES OF ROD PROBES

Diameter d (mm)	Specific statical resistance on surface shaft f_c(kg/sq.cm.)	Convergence factor K_c	Diameter d (mm)	Specific static resistance on surface shaft f_c(kg/sq.cm.)	Convergence factor K_c
62	0.98	1.04	62	1.14	1.00
27	0.94		89	1.14	
89	1.13	1.14	62	1.09	1.10
27	0.99		27	0.99	

These experiments showed that the convergence factor of the specific resistances of the rod probe side surface does not exceed 1.14, whereas the ratio of the diameters is 1 : 2.3 : 3.3. Thus the specific resistances are independent of the cross-sectional dimensions of the probes.

On the basis of these investigations we have developed a new method for determining the resistance of piles called the combined sounding method (Shashkov, Bulichev, and Mikheyev) and differing from the existing methods of sounding in that the probes are driven in and then tested under a vertical static load similar to the testing of piles, whereas with static sounding the probes are pressed into the soil and the pressing force is influenced by the time factor (Kahl and Muhs, 1952).

The use of this analogy is based on the specific resistances both of the side surface and the lower end of the pile depending, mainly, on the properties of the soil surrounding the pile, and not on the cross-sectional dimensions of the probes.

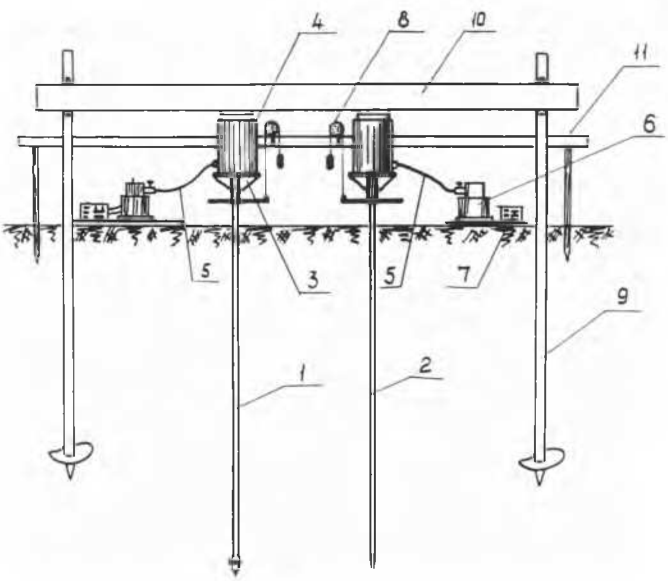

FIG. 1. Diagram of installation for testing probes under static load: 1. probe with widened cone, diameter 74 mm; 2. rod-type probe with diameter of 50 mm; 3. support on hydraulic jack; 4. hydraulic jack; 5. oil pipe; 6. pump with automatic oil delivery; 7. electrical starter; 8, deflection gauge for measuring settlement; 9. screw anchor piles; 10. supporting beam; 11. support for deflection gauges.

Further checking of these findings was carried out under field conditions at several sites with various soil conditions. The field investigations of the resistance of piles were performed by the following method of combined sounding. Two probes, one with a widened end-piece (cone) and the other of the rod type, were driven into the soil by a pile hammer weighing 80 kg and falling from a height of 80 cm. These probes were then tested under a static vertical load with the aid of the special installation shown in Fig. 1.

During the static tests of probes the load was increased in stages of 125 to 250 kg each and brought up to the critical value, where possible. The load of each stage was applied until the settlement caused thereby became conditionally stabilized, i.e. the settlement increased not more than 0.1 mm during two hours. The settlement was measured every 15 min by means of deflection gauges secured on a rod and recorded in a log. The results of the tests are used to plot curves showing the relationship between settlement and load. Fig. 2 illustrates the testing of probes under a static load.

FIG. 2. Testing of probes under static load.

As a result of combined sounding the static and dynamic resistances of the probes were determined. The specific static resistance, σ_k, of the cone during the static test is determined by means of the formula

$$\sigma_k = P_k/F_k, \tag{2}$$

where P_k is the static load on the probe with the widened cone and F_k is the cross-section area of the cone.

The specific static resistance on the side surface f_c will be

$$f_c = (P_c - \sigma_k F_c)/U_c l_c, \tag{3}$$

where P_c = static load on rod probe; F_c = cross section area of end of rod probe; U_c = perimeter of rod probe end cross-section; l_c = depth to which rod probe is driven into soil.

The specific dynamic resistance of the cone σ_d is determined from the formula

$$\sigma_d = R_k/F_k, \tag{4}$$

where R_k is the total dynamic resistance of probe with widened cone. The specific dynamic resistance on the shaft surface is determined from the formula,

$$r_d = (R_c - \sigma_d F_c)/U_c l_c, \tag{5}$$

where R_c is the total dynamic resistance of rod probe. The resistances R_k and R_c are determined from Gersevanov's formula:

$$R_{k(\text{or } c)} = \frac{nF_{k(c)}}{2}\left[\sqrt{\left(1+\frac{K}{S}\cdot\frac{4QH}{nF_{k(c)}}\cdot a\right)}-1\right], \quad (6)$$

where Q = weight of pile hammer; H = height from which hammer drops; K = number of blows in a standard series; S = settlement caused by one series of blows; $a = (Q + 0.3q)/(Q + q)$, where q is the weight of the probe; n = a factor equal to 22 kg/sq.cm. for a steel probe and pile hammer (Sokolov and Shashkov, 1949). The remaining designations are indicated elsewhere.

After determining the specific resistances of the end and the side surface of the probes the bearing capacity of reinforced concrete piles was determined. The resistance of the piles in accordance with the results of static tests of the probes is calculated from the formula

$$P_{pcb} = \sigma_k F_{cb} + U_{cb}\cdot l_{cb} f_c. \quad (7)$$

The resistance of the piles in accordance with the results of driving the probes is determined from the formula

$$R_{pcb} = \sigma_d F_{cb} + U_{cb} l_{cb} r_d \quad (8)$$

where F_{cb} = cross-section area of pile; U_{cb} = perimeter of pile; l_{cb} = design (or actual) depth to which piles are driven into soil.

Fig. 3 contains curves that are the results of probe tests at one of the sites.

Near the sounding sites, load tests of reinforced concrete piles with a section of 24 cm by 24 cm by 4 m long and 30 cm by 30 cm by 6 m long were carried out in stages of 2.5 to 5 tons. When possible the load was brought up to the critical settlement. Fig. 4 shows curves obtained from testing reinforced concrete piles with a section of 24 by 24 cm and 4 m long under a static load. Curves showing the settlement of the probes and piles when tested under trial loads were plotted for each site.

The numerical values of the pile resistances calculated on the basis of the results of combined sounding, viz. static ones from Eq 7 and dynamic ones from Eq 8, were compared with the values of the pile resistance obtained from static

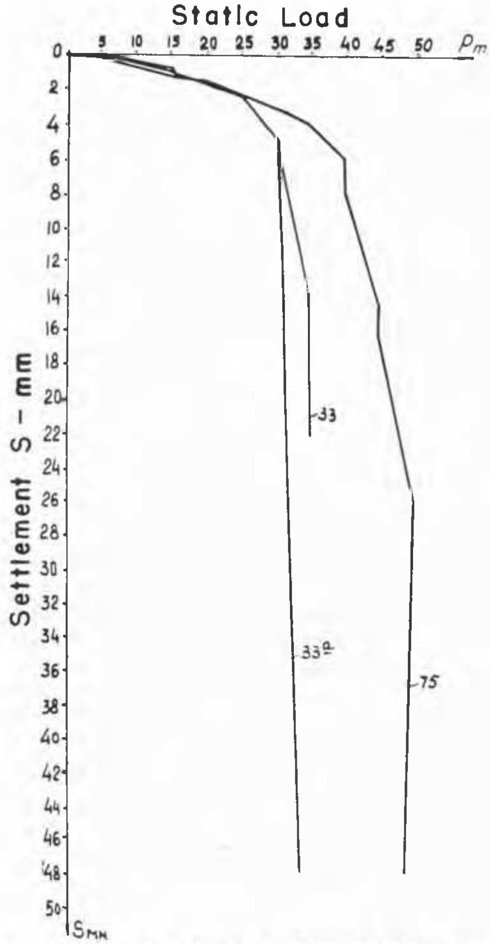

FIG. 4. Curves showing relationship between settlement of reinforced concrete piles and static load. Tests 33, 33a, 75.

testing of the piles by determining the dimensionless convergence factor $K_{c(\text{or } d)}$ from the formulae:
for static resistance

$$K_c = P_{cb}/P_{pcb}, \quad (9)$$

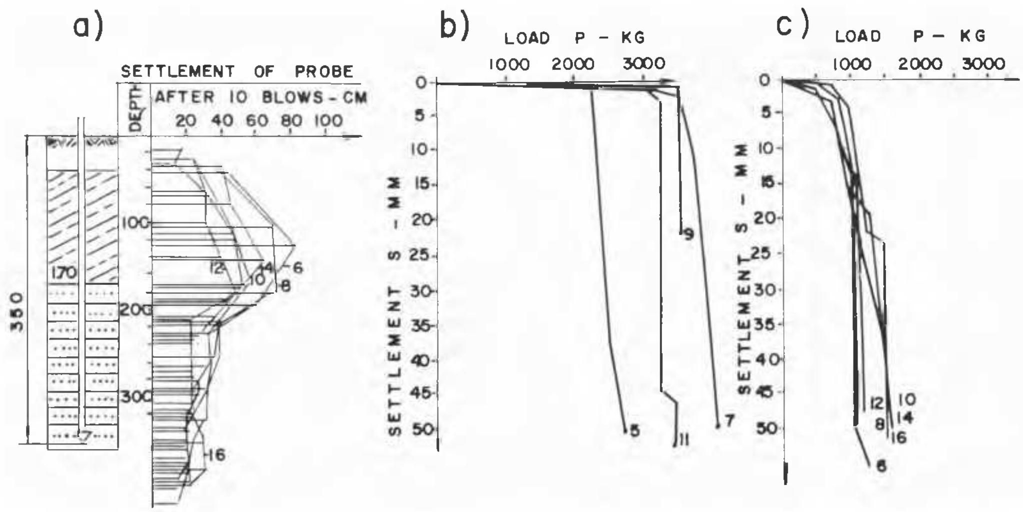

FIG. 3. Curves of probe settlement: (a) settlement of probe with widened cone with a diameter of 74 mm after 10 blows of hammer, tests 6, 8, 10, 12, 14, 16; (b) settlement of rod-type probe under static load, tests 5, 7, 9, 11; (c) settlement of probe with widened cone with a diameter of 74 mm under static load, tests 6, 8, 10, 12, 14, 16.

where P_{cb} = resistance of pile determined by testing it under static load; P_{pcb} = resistance of the same pile determined by calculations on the basis of the results of combined sounding, from Eq 7.
for dynamic resistance

$$K_d = P_{cb}/R_{pcb}. \tag{10}$$

For the most characteristic sections of the settlement curve (the proportional limit and the critical load) tables, comparing the resistance of piles obtained from their testing under a static load P_{cb} and the resistance P_{pcb} calculated from Eq 7 (Table II for the proportional limit and Table III for the critical load), have been compiled.

Tables comparing the dynamic resistances have not been included in this report.

The average values of the convergence factor K_c are as follows: for the proportional limit K_c = 0.87 to 1.12; for the critical load K_c = 0.95 to 1.22.

Below are given the results of similar investigations of the resistance of piles by means of sounding carried out at other sites.

At a site near Leningrad the subsoil consisted of (from the surface downward) dusty sand, peaty sandy loam, and varved water-saturated loam with thin intermediate layers of sand. The average value of the specific static resistance on the probe side surface f_c was 0.233 kg/sq.cm., and that of the reinforced concrete friction piles with a section of 35 cm by 35 cm and 12 to 13 m long was 0.253 kg/sq.cm. Thus the convergence factor, K_c = 1.09.

At a site near Moscow where the soil consists of a variety

TABLE II. RESISTANCE OF PILES OBTAINED WHEN TESTING UNDER STATIC LOAD AND CALCULATED ACCORDING TO SPECIFIC RESISTANCES OF PROBES

Site	Testing of reinforced concrete piles under static load					Specific resistance (kg/sq.cm.)		Resistance of piles calculated from Eq 7 (tons)			Convergence factor	Remarks
	Cross section area, F_{cb} (sq.cm.)	Driving depth, l_{cb} (cm.)	Shaft surface area, $U_{cb}l_{cb}$ (sq.cm.)	Load at proportional limit, P_{cb}(tons)	Settlement, S (cm.)	cross section, σ_k	side surface, f_c	end P_0	side surface P_b	total P_{pcb}	$K_c = \frac{P_{cb}}{P_{pcb}}$	
	576	370	35,520	35.0	0.41	19	0.467	10.9	16.59	27.53	1.371	Friction piles.
1	576	340	32,640	25.0	0.26	19	0.467	10.9	15.24	26.19	0.955	Interstratification of
	576	240	29,040	25.0	0.26	19	0.467	10.9	13.56	24.51	1.020	dark gray clay with
								Average value of K_c = 1.12				fine sand.
												Consistency B = 0.5
	900	439	25,680	55.0	0.55	24	0.494	21.60	26.02	47.62	1.155	Friction piles.
2	576	366	35,232	40.0	0.41	24	0.494	13.82	17.41	31.23	1.281	Morainic loam with
	576	369	25,424	20.0	0.38	24	0.494	13.82	17.50	31.32	0.639	boulder and gravel
												inclusions, hard-plastic.
												Consistency,
								Average value of K_c = 1.03				B = 0.3–0.5
	900	555	66,600	30.0	0.105	24	0.180	21.60	11.99	33.59	0.898	Friction piles.
3	900	482	57,840	25.0	0.329	24	0.180	21.60	10.41	32.01	0.781	Morainic loam, dense
	576	290	27,840	25.0	0.84	24	0.180	21.60	5.01	26.61	0.939	with nests of sand.
								Average value of K_c = 0.87				B = 0.3–0.5
4	900	335	40,200	45.0	0.56	59	0.239	53.10	9.61	62.71	0.633	End-bearing piles.
	900	205	24,600	60.0	0.47	59	0.239	53.10	5.88	58.98	1.017	Hard-plastic loam
												with boulder and
												gravel inclusions.
								Average value of K_c = 0.84				Consistency, B = 0.3

TABLE III. RESISTANCE OF PILES OBTAINED WHEN TESTING UNDER STATIC LOAD AND CALCULATED ACCORDING TO SPECIFIC RESISTANCES OF PROBES

Site	Testing of reinforced concrete piles under static load					Specific resistance (kg/sq.cm.)		Resistance of piles calculated from Eq 7 (tons)			Convergence factor	Remarks
	Cross section, F_{cb} (sq.cm.)	Driving depth, l_{cb} (cm.)	Shaft surface area, $U_{cb}l_{cb}$ (sq.cm.)	Maximum load, P_{cb} (tons)	Settlement, S (cm.)	cross section, σ_k	side surface, f_c	end P_0	side surface, P_b	Total, P_{pcb}	$K_c = \frac{P_{cb}}{P_{pcb}}$	
	576	370	35,520	50.0	4.82	30	0.50	17.36	35.04	35.04	1.427	Friction pile.
1	576	340	32,624	35.0	5.59	30	0.50	17.28	16.31	33.59	1.042	For soils, see Table II.
	576	240	23,040	35.0	6.39	35	0.50	20.16	11.52	31.68	1.105	
								Average value of K_c = 1.22				
2	576	366	35,232	50.0	1.61	42	0.422	24.19	14.87	38.06	1.314	Friction pile.
	576	369	35,424	30.0	6.8	42	0.422	24.19	14.95	39.14	0.766	For soils, see Table II.
								Average value of K_c = 1.04				
	900	555	66,600	50.0	1.09	44	0.022	39.60	14.79	54.39	0.921	Friction pile.
3	900	482	66,960	35.0	4.22	44	0.222	39.60	14.87	54.39	0.643	For soils see Table II.
	576	290	27,840	40.0	5.6	44	0.222	25.26	6.18	31.44	1.272	
								Average value of K_c = 0.95				

of lake and swamp deposits (sandy loam, loam, clay, silt, and peat) the method of combined sounding was employed to investigate the resistance of piles with a section of 30 cm by 30 cm and a length of 6 to 9 m. The convergence factors of the static resistances of the piles, $K_c = 1.11$ to 1.12.

At another Moscow site in 1961–62 experimental investigations were carried out, by means of the method described above, to determine the resistance of reinforced concrete piles with a section from 26 cm by 26 cm to 40 cm by 40 cm, driven into the soil to a depth of 5.5 to 9.0 m and tested under a static test load. The soil at the site is comprised of a top layer of loam lying on morainic loam and clay. The average convergence factor of the static resistances of piles, determined from Eq 9 was $K_c = 0.95$ to 0.99.

It should be noted that the most reliable results are obtained with the static testing of probes, and we would therefore recommend that the determination of the bearing capacity of piles be done by using this procedure.

Values of the factor K_c close to unity confirm the basic assumption that the specific resistances of the lower end and the surface of the pile practically do not depend on its cross-sectional dimensions.

Before accumulating data on the investigations of the resistance of piles by means of the combined sounding method, however, the factor K_c should be used and the resistance of friction piles determined by the formula

$$P_{pcb} = \bar{K}_c(F_{cb}\sigma_k + U_{cb}l_{cb}f_c) \tag{11}$$

where K_c is a factor equal to 0.9–1.20 (for friction piles). The smaller value of K_c is taken for piles, the lower ends of which rest on dense soil, and the larger value for those on soft soil. The safe load on a pile is determined from Eq 11 with an additional factor $K_o = 0.70$ (in accordance with the Construction Norms and Rules, 1962).

If the specific resistances of the cone are equal to or greater than the safe resistance of the pile material, its bearing capacity should be determined as for an end-bearing pile according to the corresponding design requirements as a centrally compressed element (without any account taken of longitudinal bending).

When determining the resistance of a pile according to the given settlement the specific resistances calculated in accordance with the resistance corresponding to this settlement are introduced into the calculations.

CONCLUSIONS

1. The specific resistances of piles to vertical loads depend upon the properties of the soil surrounding the pile and not upon the cross-sectional dimensions of the pile.
2. The method of determining the bearing capacity of a pile by combined sounding is economical and can replace to a certain degree the time-consuming load tests of piles.

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