ISSN 1846-6168
UDK 624.131.38

DIFERENCIJALNA METODA OCIJENIVANJA KARAKTERISTIKA TLA PREMA REZULTATIMA ISPITIVANJA PILOTA

DIFFERENTIAL METHOD OF ESTIMATION OF SOIL RESISTANCE CHARACTERISTIC ACCORDING TO THE RESULTS OF THE PILE TESTS

Yuri Tugaenko, Anatoly Tkalich, Michael Marchenko, Ludmila Loginova

Professional paper

Abstract: *Piles testing for determination of their bearing capacity performs by applying a load with measurement of the value of settlement on its head. By standard pile test, it is impossible to determine the value of shear resistance along the shaft of a pile and a compression below its toe. The new test procedure allows to determine the values of these characteristics. Tests were performed using equipment for standard pile tests. The essence of the developed method is to use the elastic properties of the soil and pile material to estimate characteristics of soil resistance. For this purpose, instead of the stepwise-increasing method was applied cyclically increasing load. Each stage represents an independent cycle, consisting of the load application, holding it up to the stabilization of strains and unloading stage.*

Keywords: *pile; load; shift; compression; structural strength*

Stručni članak

Sažetak: *Ispitivanja nosivosti pilota provodi se tako da se na glavu pilota aplicira opterećenje te se tijekom tog opterećenja mjeri slijeganje njegove glave. Prema rezultatima standardnih ispitivanja nije moguće odrediti vrijednost smicanja uzduž podzemnog djela oplošja pilota a niti kompresiju ispod vrha. Nova, predložena u ovom radu, metoda ispitivanja omogućuje određivanje tih traženih karakteristika. Ispitivanja se provode uz pomoć standardne opreme koja se koristi za ispitivanje pilota. Suština razrađene metode je u korištenju elastičnih svojstava tla i materijala pilota za određivanje parametara čvrstoće tla. Sukladno tome, umjesto stupnjevito rastućeg opterećenja primjenjuje se ciklički rastuće opterećenje. Svaki stupanj je zapravo samostalni ciklus koji se sastoji od nanošenja opterećenja, njegovog zadržavanja do trenutka stabilizacije slijeganja te rasterećenja.*

Ključne riječi: *opterećenje, pilot, strukturna čvrstoća, tlak*

1. INTRODUCTION

Pile is deep foundation construction that transfer the load from the construction deep into the soil massif. Its bearing capacity is determined by sum of shear resistance along the shaft surface and compression under the pile toe.

According to Ukraine current regulations, a preliminary value of the maximum load on the pile calculate by using tabulated values of shear and compression resistance, depending on the composition and condition of soil. Calculated values must be adjusted according to results of pile tests in natural conditions. Control tests of piles on construction site performs on 0.5% of piles, but at least on two. The current standard requires determination of the pile ultimate load without taking into account soil resistance characteristics.

In the Odessa State Academy of Civil Engineering and Architecture was developed a new test method that allows to determine the resistance characteristics of soils using standard equipment for static tests. Its essence is in considering of elastic properties of reinforced concrete piles to determine the limits of soil resistance.

2. METHODOLOGY

Pile surrounded by soil, which is compacted in the process of its installation. The shear resistance by surface of the pile shaft limits compressed portion of the pile length. Therefore, each stage of load corresponds to a certain portion of the pile length, in which its elastic deformation observed. With increasing of load, compressed portion of length increases. Increasing of pile length portion $\Delta l_{f,i}$ from the next stage is influenced by the respective load increment ΔP_i. This happens because at the higher interval of shaft length value of limit shear resistance are preserved, which proved earlier by field studies [1; 2].

Elastic deformation consist of two parts - elastic and viscoelastic. Groundwater environment surrounding pile shaft is viscoelastic. The elastic part of the deformation disappears at once, almost immediately after removal of the load, but reduction of viscoelastic component continues for a long time [3].

In the New method, changes in technology of the load application are proposed. Instead of stepwise increasing, provided by current standard methodology applied cyclically increasing load. Each stage is an independent cycle consists of load applications, its keeping to the stabilization of settlement and unloading stage. At each stage total and residual value of settlement is measured. According to its difference, elastic part of pile settlement is determined. Dependence of instant- elastic deformation on the load measured during 10 - 15 minutes after its removal is used in applied technique.

According to the test results we get graph of elastic component settlement in dependence of load $s_y = f(P)$. Graph consists of two branches: first describes the elastic compression of pile shaft, second - is the sum of an elastic compression of pile shaft and the compression below the toe. Breakpoint corresponds to load equals to limit shear resistance Pf along the underground pile shaft surface A_f. The resulting relationship is the starting point for estimation of the soil resistance characteristics. Starting point is displaced from the start of the axes, since it does not take into account viscoelastic deformation of the elastic component.

Elastic component in dependence of pile top settlement on load is the result of an elastic compression of pile shaft. The length of the compressed portion by depth l_f depends on the magnitude of the applied load Pi and soil shear resistance fi on pile shift interface with soil A_f. The lower is shear resistance, the greater the length of the compressed portion.

In the practice of studies of stress-strain state of the pile-soil system two methods to estimate the shear resistance are used: integral and differential. By integral method we get the mean value of the shear resistance across the surface. With this purpose performs pulling out tests of pile using stamp piles, et al. [4]. By differential method, we get shear resistance in some parts of the length of the pile shaft when applied tensile piles, tensor instruments, strain gauge et al. [4; 5].

2.1. Determination of shear resistance of the pile shaft surface

Using the procedure of cyclically - increasing load, shear resistance along the shaft surface can be estimated as mean value of f along the pile and in some areas of its length Δf_i. The mean value of the shear resistance is equal to the quotient of the load P_f and the surface area of the shaft surfasace A_f, formula 1:

$$F = \frac{P_f}{A_f} \tag{1}$$

The limit load P_f determined by the intersection of the first and second branch of elastic component of its settlement in the graph of load dependence, Fig. 1.

The shear resistance of any portion of the shaft length can be determined by the values of either the elastic modulus of the pile material, or the strain in its elastic compression.

2.2. Estimation of shear resistance using elastic modulus values

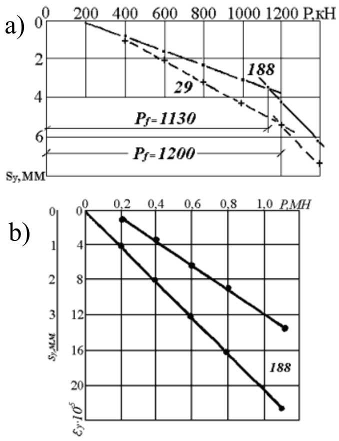

Figure 1. a) Graphs of settlement elastic component dependence on the load; b) Graphs of elastic settlement (s_y) and the relative deformation (E_y) dependence on the load. The numbers shown numbers of piles on construction site.

The modulus of elasticity of reinforced concrete piles at a load equal to the limit shear strength P_f is determined by the formula 2:

$$E_y = 0{,}5 \cdot \frac{P_f \cdot l_f}{d^2 \cdot s_y} = \sigma_{cp} \cdot \frac{l_f}{s_y} \tag{2}$$

where: P_f - load equal to the limit of shear resistance by the pile shaft surface; lf - the length of the underground part of the pile; d^2 – its cross-section area; s_y - elastic component of settlement, at a load P_f; $\sigma_{cp} = 0.5 \cdot P_f / d^2$ - average stress value in the cross section a pile.

Taking assumption about equality of elasticity modulus within the pile length, we can determine the length of the compressed portion length of each load stage by Equation 3:

$$l_{f,i} = \frac{E_y \cdot s_y}{\sigma_{cp}} \tag{3}$$

2.3. Estimation of shear resistance using the values of relative deformation

The strain of the pile shaft elastic compression at the limit shear resistance along its surface is determined by the ratio of the elastic settlement and pile length by formula 4:

$$\varepsilon_y = \frac{s_y}{l_f} \tag{4}$$

By the obtained data, we can draw the graph of dependence of the elastic settlement and strain on load (Fig.1.b). For the elastic component of settlement graph is drawn using the results of measurements at every stage of the loading, and for the strain - with two points: the origin and end value of P_f. By the graphs on Fig. 1b the length of the compressed portion is defined for any load P_i by formula 5:

$$l_{f,i} = \frac{s_{y,i}}{\varepsilon_{y,i}} \tag{5}$$

Using formula (5) graph $l_f = f(P)$ can be drawn, by which value of the limit shear resistance is determined at any portion of the length of the pile shaft Δl_f, by the formula 6:

$$\Delta f_i = \frac{\Delta P_f}{\Delta l_{f,i}} \cdot u \tag{6}$$

where: u is perimeter of the pile.

According to the obtained values graph of changes in shear strength along the length of the pile shaft can be drawn.

As examples two pile test results are given, with cross sections 0.35 x 0.35 m and length 16.0 m and 15.0 m in Ilyichevsk city and the Yuzhni city of Odessa region [4; 10]. Parameters of soil properties based on investigation in situ presented in Table. 1, and the geological structure in Fig. 2, b, d. Geological column shown from the bottom level of the construction pit with depth of 3.5 and 1.0 m.

Table 1. Parameter of soil properties of loess soil strata

No	Type of soil	ρ_s g/cm³	ρ_d g/cm³	w_L -	w_P -	S_r -	E, MPa	φ,°	c, kPa
Ilyichevsk city of Odessa region (pile No 188)									
2	loam	2,69	1,44	0,34	0,21	0.68	14/8	22	22
3	sandy loam	2,67	1,40	0,25	0,18	0.81	4	17	8
4	loam	2,68	1,42	0,33	0,21	0,72	13	22	22
5	sandy loam	2,67	1,40	0,26	0,18	0,80	4	17	8
6	loam	2,68	1,41	0,30	0,20	0,62	10	17	15
7	sandy loam	2,67	1,40	0,25	0,18	0,80	4	17	8
8	loam	2,72	1,53	0,38	0,23	0,80	16	23	25
9	clay	2,73	1,63	0,40	0,22	0,81	23	19	50
Yuzhni city of Odessa region (pile No 29)									
2	loam	2,70	1,50	0,33	0,21	0,68	12/8	20	24
3	sandy loam	2,69	1,46	0,28	0,20	0,93	4	20	6
4	loam	2,70	1,61	0,34	0,22	0,96	13	18	23
5	sandy loam	2,69	1,54	0,28	0,20	0,87	7	15	9
6;6a	loam	2,72	1,57	0,42	0,26	0,93	14	21	35
7	clay	2,73	1,55	0,46	0,27	0,93	20	18	30

Note: The soil surrounding the piles is loess soil strata composed of loam and sandy loam with a high level of groundwater.

The measurement results of the elastic settlement component in dependence on load are shown in Table. 2. By the obtained data graphs of dependencies are drawn in Figure 1.

The elastic deformation along the length of pile shaft is uneven and depends on the shear resistance of the soil layers, which the pile passed. When the load increments are equal in layers with lower shear resistance increment of compressed length portion is greater than in the layers with large values. Fig. 2a. shows the dependence of the compressed length portion on the load.

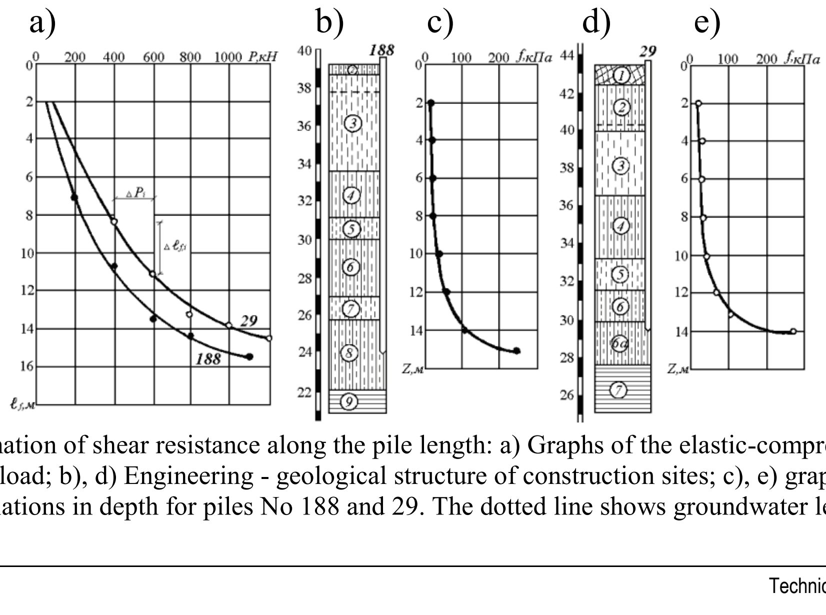

Figure 2. Determination of shear resistance along the pile length: a) Graphs of the elastic-compressed length portion dependence on the load; b), d) Engineering - geological structure of construction sites; c), e) graphs of shear strength variations in depth for piles No 188 and 29. The dotted line shows groundwater level.

From the graph on Fig. 2, it can be determine the shear strength anywhere on the length of the pile shaft by the formula 5. On Fig. 2, c), e). Given its values along the pile length determined by the results of investigation.

2.4. Estimation of ultimate compressive strength and structural strength

The pile shaft, after it installation is surrounded by compacted soil around the shaft and the compacted core under the toe. The scheme of the soil state of the lower part is shown in Figure 3c). When the load exceeds the limit shear resistance at the side surface, $P > P_f$, there are elastic and permanent deformations below the pile toe. In clay soils in process of compacted core formation occurs increase in the density of the soil skeleton and the reduction of structural strength, which value is lower than in natural soil [6]. That is why, the residual strain occurs within the compacted core until the load at which stress at the boundary of the compacted zone are equilibrated with structural strength of the surrounding soil. For the loess sandy loam and loam the depth of compacted core H_{com} is in range 1,9 - 2,0 d [7 - 10; 12]. Then the stress at the lower boundary of the compacted zone will be equal to:

$$\sigma_{zp} = \alpha \cdot \frac{P_R}{d^2} \tag{7}$$

where: α - coefficient taking into account change of additional pressure in the ground by depth (Fig. 3e) its value is defined by the DBN [13].

Soil testing by piles with the application of vertical pressed and pull out loads performed on four location of the construction site of residential buildings on crossing of the Zatonsky str. and Crimean Boulevard in Odessa. Piles with a cross section of 0.35 m and a length of 12.0 m were tested.

Table 2. Parameters of pile shaft and soil deformation

No of a pile	*P, MN*	s_y, *cm*	$\ell_{f,i}$, *cm*	ΔP_i, *kN*	$\Delta \ell_{f,i}$, *cm*	f_i, *kPa*
Ilyichevsk city of Odessa region						
188	0,2	0,029	699	200	699	20,4
	0,4	0,085	1052	200	353	40,5
	0,6	0,16	1336	200	284	50,3
	0,8	0,226	1419	-	-	-
	1,13	0,346	1540	530	204	185,6
					1540	1130
Yuzhni city of Odessa region						
29	0,4	0,103	822	400	822	34,8
	0,6	0,210	1144	200	322	44,4
	0,8	0,319	1312	200	168	85,0
	1,0	0,420	1382	-	-	-
	1,2	0,527	1440	400	128	223,2
					1440	1200

The geological structure on the two test sites on opposite sides of the site are shown in Fig. 3, a) and b), while parameters of soils shown in the Table. 3. The groundwater level in the test period was at the depth of 1.8 m below soil surface (0.4 - 0.6 m below the bottom of the construction pit).

According to the research the values of limit load Fu and structural strength p_{str} of bearing soil layer are determined. To this purpose, after reaching the critical load at its constant value there is undamped increase of settlement, the load is maintained until reaching 5.0 - 7.0 mm of settlement value, and then pumping oil into the jack stops. As a result of stress relaxation significantly reduced the duration of the deformation stabilization. The value of the load after reaching equilibrium is a limit value and counterbalanced with sum of shear resistance along the shaft surface (P_f) and compression below the pile toe (P_R) and is determined by the formula 8:

$$F_u = P_f + P_R \tag{8}$$

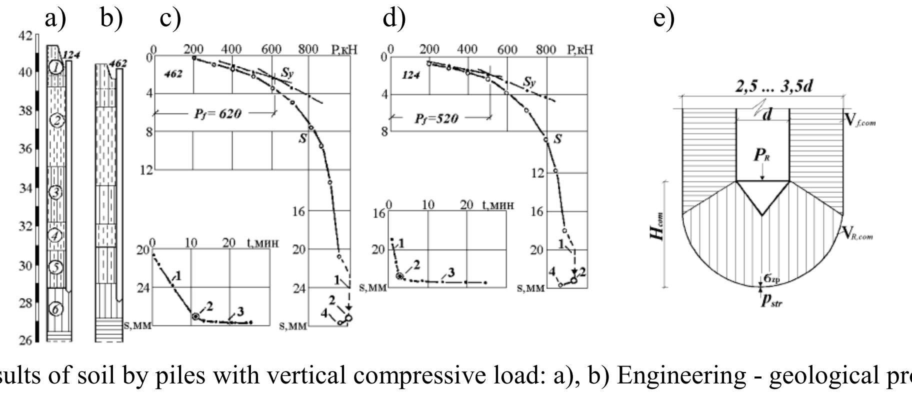

Figure 3. Test results of soil by piles with vertical compressive load: a), b) Engineering - geological profile sections of the test piles; c) and d) Graphs of settlement dependence on load. 1. Pile 'jump' failure. 2. Completion of pumping the oil into chamber of the jack. 3. Process of load reduce and strain stabilization. 4. The load counterbalanced by the resistance of the soil; e) Groundwater level after pile installation. $V_{f,com}$ - the volume of compacted soil around the pile shaft. $V_{R,com}$ - compacted soil core below the pile toe.

Structural strength is equal to the voltage at the border of the compacted core of the limit value of the load on the tip of the pile P_R. The results of determinations are shown in Table. 4.

Fluctuations of the structural strength values according to the pile test results for the IGE-6 (240 - 330 kPa) closely coincide with the results of the experimental determination 250 kPa [11].

Table 3. Parameters of soil properties

No	Soil type	ρ_s g/cm³	ρ_d g/cm³	w_L -	w_P -	S_r -	E, MPa	φ, °	c, kPa
Odessa city (pile No 24 and 624)									
1	loam	2,70	1,41	0,32	0,20	0,62	6	18	15
2	sandy loam	2,69	1,38	0,27	0,19	0,79	3	15	6
3	loam	2,69	1,53	0,29	0,17	0,78	7	17	18
4	sandy loam	2,70	1,52	0,28	0,19	0,80	5	16	9
5	loam	2,71	1,57	0,33	0,18	0,82	10	19	24
6	loam	2,71	1,59	0,35	0,19	0,85	12	20	36
7	clay	2,73	1,58	0,40	0,21	0,90	15	20	41

Table 4. Soil resistance properties by pile tests

No of pile	P_{lim}, kN	$P_{кр.}$, kN	F_u, kN	P_f, kN	P_R, kN	P_R/d^2, kN	p_{str}, kN	$p_{str,cp.}$, kPa
124	900	950	880	520	360	2939	317	293
404	850	900	850	580	270	2204	238	
462	950	1000	950	620	330	2694	291	
129	900	950	930	570	370	3020	326	

2.5. Reliability of soil resistance characteristics according to soil tests by piles with cyclically - increasing load method

The reliability of the applied method for determining the average value of the shear resistance along shaft surface was confirmed by results of tests on piles with compression and pull out load [4].

Tests on vertical pulling load performed close to pile No 462 was made twice, Fig. 4. For the first time in 11 days after an installation and again after an interval of 12 days. The test results are shown in Table 5.

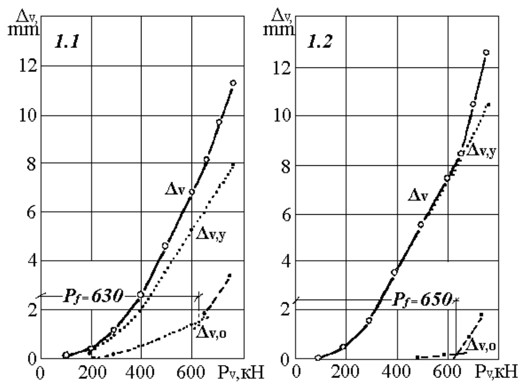

Figure 4. The results of pile testing on the vertical pull out load: 1.1 - the first test; 1.2 – repeated test

Table 5. The shear resistance along pile shaft surface

No of Building	No of pile	P_f, kN	l_f, m	A_f, m²	P_f + $G_{св}$ kN	P_f - $G_{св}$ kN	$f_{ср.}$, kPa
3	124	520	11,67	16,3	555	-	34
3a	404	580	11,58	16,2	615	-	38
7	462	620	11,38	15,9	655	-	41
8	129	560	11,56	16,2	595	-	37
7	1.1	630	11,52	16,1	-	595	37
7	1.2	650	11,52	16,1	-	615	38

Notes: P_f - limit load counterbalanced by lateral surface of the pile; l_f and A_f – length and area of the underground part of the pile lateral surface; G_{sv} - pile weight of 35 kN; f_{sr}. - average value of shear resistance along the lateral surface

Research are performed by the method of cyclically increasing load. When tested on pull out load tensile force taken by reinforcement of the pile in the elastic deformation stage. At the first test, there were considerable residual deformation, which can be explained by the appearance of micro-cracks in the pile concrete at the contact with the reinforcement when the pull out load was applied.

At repeated testing the residual deformation was part of a millimeter. The dependence of the residual strain on the load has two branches. First describes joint deformation of reinforcement and pile concrete, and second defines pile pulling out of the soil. Their intersection fixes the load corresponding to the beginning of pile "pulling out" of soil. Resulting load value minus the weight of the pile determines the limit value pull out load, by which was determined average value of shear resistance along the surface of the pile shaft. The results are shown in Table 5. The discrepancy between the results of the limit shear resistance along the shaft surface by the results of compress and pull out tests of two adjacent piles was about 8%.

3. CONCLUSION

1. Method of cyclically - increasing load allow to determine a number of parameters of the stress-strain state of the pile - soil subgrade system

2. Its application is possible using standard equipment and requires no additional equipment and measuring systems.

3. The validity of the results verified by field investigations.

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Author contact:

Yuri Tugaenko, Prof. Dr. Tech. Sci.
Odessa State Academy
of Civil Engineering and Architecture
65029 Odessa, Didrihsona 4, Ukraine

Michael Marchenko, PhD.
Odessa State Academy
of Civil Engineering and Architecture
65029 Odessa, Didrihsona 4, Ukraine

Anatoliy Tkalich, PhD.
Odessa State Academy
of Civil Engineering and Architecture
65029 Odessa, Didrihsona 4, Ukraine

Ludmila Loginova, PhD
Odessa State Academy
of Civil Engineering and Architecture
65029 Odessa, Didrihsona 4, Ukraine
e-mail: milaloginova@ukr.net