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Impact Dipping Pyramidal-Prismatic Piles and their Resistance to Pressure and Horizontal Load

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Abstract

The results of experiments carried out in the field with the use of large-scale models of reinforced concrete driven pyramidal - prismatic piles with different lengths of the pyramidal part are presented. The impact capacity of piles were evaluated of their bearing capacity to the action of indentation and horizontal static loads. It has been established that the driving of pyramidal-prismatic piles is accompanied by both large (by 1.10–1.60 times) and lower (by 8.0–37.0 %) energy consumption for their driving in comparison with conventional prismatic and pyramidal piles. It was also revealed that under the action of a vertical indentation load, the bearing capacity of the pyramidal-prismatic piles is 1.09–1.48 times, and under the action of a horizontal static load, it is 1.17–1.80 times higher than that of a prismatic pile. It has been established that with an increase in the length of the pyramidal part of the test piles, there is an increase in their bearing capacity by 1.12–1.34 times. Formulas are proposed for determining the bearing capacity of pyramidal-prismatic piles. The research results serve as the basis for the development of recommendations for the calculation and design of pyramidal-prismatic piles.

Keywords

model, pyramidal - prismatic pile, soil, driving, testing, load, settlement, bearing capacity

1 Introduction

As it is known, prismatic and pyramidal piles are widely used in the practice of pile foundation construction. Prismatic piles, as a rule, are some what inferior in bearing capacity to pyramidal piles. So the bearing capacity of pyramidal piles, depending on the angle of inclination of their lateral faces, is 1.35–2.5 times higher than the bearing capacity of prismatic piles [1]. But the energy consumption of piling hammers for driving pyramidal piles is 2–3 times higher than for prismatic piles, which is accompanied by a decrease in the productivity of hammers and an increase in the duration of driving pyramidal piles [2]. Consequently, the prismatic piles, yielding to the pyramidal piles in terms of bearing capacity, have significant advantages over them in terms of energy consumption and driving time. As it can be seen, the indicated differences in the behavior of the considered piles are due to their different shape of the longitudinal section.

Based on this, it is obvious that it is relevant to create a pile structure of such a form that would have the advantageous properties of both prismatic and pyramidal piles in an optimal combination [3–7]. Such driven piles include pyramidal-prismatic piles developed in the geotechnical laboratory of M. Kh. Dulaty Taraz Regional University under the support of hydraulic structures [8]. These new pile structures have a combined (pyramidal - prismatic) shape, including both pyramidal (upper) and prismatic (lower) parts. Taking into account the novelty of the proposed piles, the authors carry out complex experimental and theoretical studies to study the features of their driving and work under load.

The results of the preliminary calculation performed earlier, presented in [9, 10], show that the shape of the pyramidal-prismatic piles (hereinafter referred to PPP) affects their bearing capacity, which is significantly different from the bearing capacity of pyramidal and prismatic piles.

In the framework of experimental studies at the initial stage, the authors carried out experiments using small-scale models of PPP in a soil flume (in laboratory conditions), the results of which are presented in [11, 12].

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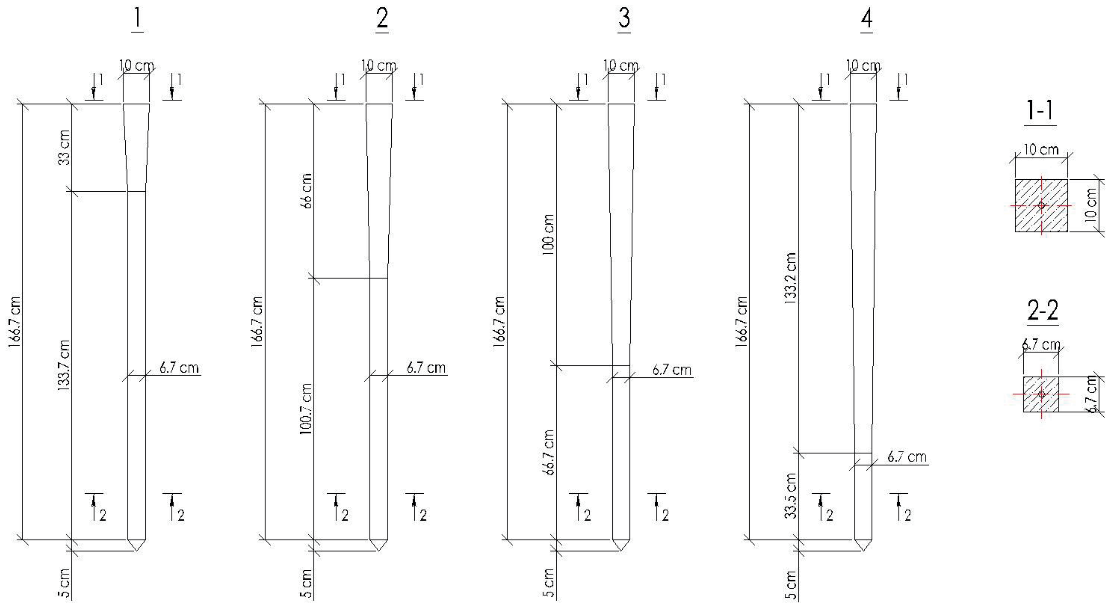
The purpose of the work is to assess the energy intensity of driving (submersion) of pyramidal-prismatic piles, as well as their resistance to indentation and horizontal loads using large-scale models in the field.

2 Characteristics of pile models, equipment, and research methods

Models of piles are made of solid one-piece reinforced concrete with tension-free longitudinal reinforcement and transverse reinforcement of the shaft. The scale of models (hereinafter referred to as piles) is taken as 1:3. Experimental piles were made with a pyramidal section from 33 cm to 133.2 cm long (Fig. 1). To compare the research results, three models were adopted as control piles: a prismatic pile with a cross-sectional size of 6.7 × 6.7 cm, a prismatic pile with a cross-sectional size of 10.0 × 10.0 cm, and a pyramidal pile with a cross-sectional size in the upper parts 10.0 × 10.0 cm and in the lower part -6.7 × 6.7 cm. The slope of the side faces of the pyramidal pile to the vertical was $i_p = 0.01$. Geometrical parameters and weight of piles are shown in Table 1.

Field tests were carried out at the test site of the production base of the South Kazakhstan branch of "Kazakh Research and Design Institute of Construction and Architecture" JSC. The experimental site, with dimensions in plan 6.0 × 3.0 m and a depth of 3.0 m. was composed of sandy loam. Site preparation was included layer-by-layer



1 – model of PPP with cross-sectional dimensions on top of 10 × 10 cm and a pyramidal section 0.2 L length; 2 – model of PPP with cross-sectional dimensions on top of 10 × 10 cm and a pyramidal section 0.4 L length; 3 – model of PPP with cross-sectional dimensions on top of 10 × 10 cm and a pyramidal section 0.6 L length; 4 – model of PPP with cross-sectional dimensions on top of 10 × 10 cm and a pyramidal section 0.8 L length

Fig. 1 Diagram of pile models

Table 1 Geometric parameters of pile models and their mass

Pile type	Geometric parameters, cm		Pile weight, N
	barrel length (spikes)	barrel cross-sectional dimensions	
Experienced piles:			
PPP 1 (with cross-sectional dimensions on top 10.0 × 10.0 cm and a pyramidal part 0.2L long);			198.1
PPP 2 (also, with a pyramidal part of 0.4 L length);	166.7 (5.0)	6.7 × 6.7	212.7
PPP 3 (also, with a pyramidal part of 0.6 L length);			226.3
PPP 4 (also, with a pyramidal part of 0.8 L length).			241.1
Control piles:			
prismatic;		6.7 × 6.7	180.50
prismatic;	166.7 (5.0)	10.0 × 10.0	386.51
pyramidal		10.0 × 10.0/ 6.7 × 6.7	258.0

Note: 1 – Before the line, the cross-sectional dimensions are indicated in the upper part, after the line - in the lower part; 2 – L is the length of the piles without the tip laying and uniform compaction of soil from the bottom of a previously dug excavation. The physical and mechanical characteristics of the soil were established by the penetration method using the PSG MG-4 device (Table 2).

Special experimental equipment was developed and manufactured for driving and testing of pile models (Fig. 2). Parameters, principles, and sequence of using this equipment are presented in [13].

The piles were driven into the ground by driving them at a constant energy of each impact. A striker weighing 40 kg was dropped from a height of 0.5 m. The pile depth was 145.0–145.5 cm (the maximum difference was 0.34 %).

Tests of pile models to assess their bearing capacity were carried out in accordance with the requirements of GOST 5686-2012. "Soils. Methods of field testing with piles" [14] by stepwise increasing loading of piles with an indentation static load with the provision of the required conditional stabilization of their settlement. Power loading of each pile was carried out to a settlement of at least 40 mm. The bearing capacity of the piles was determined in accordance with the requirements of SP RK 5.01-103-2013 "Pile foundations" [15].

3 Research results

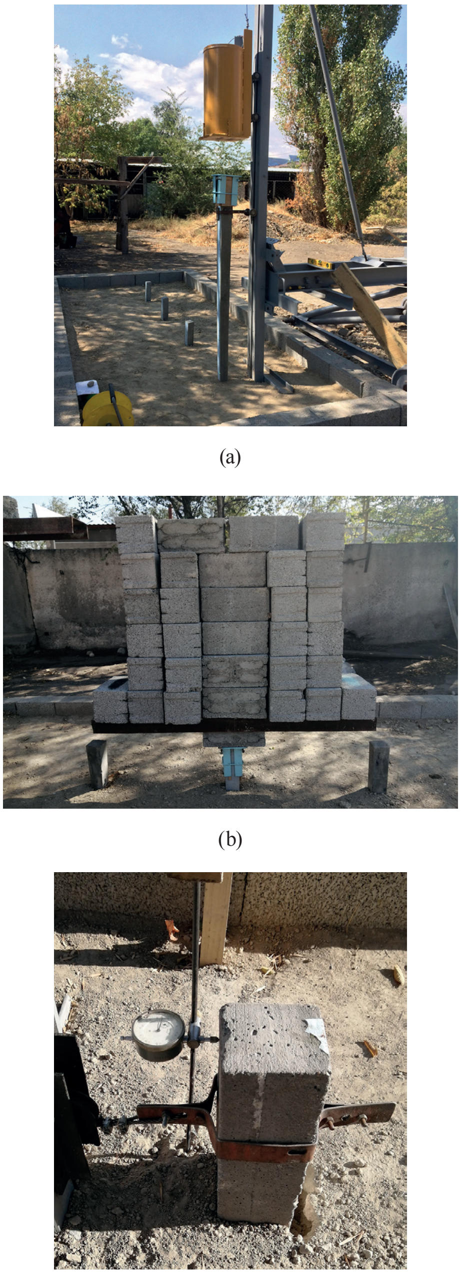
Information is about the number of blows to piles, the energy consumption of the striker for driving them, as well as the depth and volume of the submerged part of the piles are presented in Table 3. The pile driving records are shown in Fig. 3.

The assessment of the submersion and energy intensity of the pilot and control models of piles based on field tests was carried out on the basis of the following indicators:

- the number of strikes of the striker, spent on driving the pile model (Table 3);
- specific energy consumption of driving the pile model Ev, taken as the ratio of the total potential energy of the striker's impacts spent on driving the model to the volume of its submerged part in the ground (Table 3);
- the coefficient of the relative energy intensity of driving the pile model K_e, taken as the ratio of the total potential energy of strikes of the striker spent on driving the experimental model of the pile to the same energy parameter of the control model of the pile (Table 4).

Table 2 Physical and mechanical characteristics of the experimental site soil

Characteristics	The values
Humidity, W, %	3.16–5.58
Density, ρ, kg/m^3	1400–1670
Moisture at the pour point, W_m, %	24.18–24.37
Moisture at the rolling edge, W_p, %	17.30–17.47
Plasticity number, I_p	6.88–6.90
Maximum penetration resistance, P_{max}, MPa	1.47–1.62
Compaction factor, K	0.89–0.94
Index (degree) of humidity, I	0.75–0.84
Deformation modulus, E, MPa	31.6–33.6
Internal friction angle, φ, grade	17.1–17.6
Specific adhesion, c, MPa	0.018–0.019



(a)

(b)

(c)

Fig. 2 Fragments of pile driving (a) and their tests for pressing (b) and horizontal (c) loads

Table 3 Results of pile models driving

Pile type	The total energy of impacts spent on the hammering E, J (number of strokes)	Immersion depth L, cm	Submerged volume V, cm^3	Specific energy consumption of driving E_v, J/cm^3
Experienced piles:				
PPP 1 (cross-sectional dimensions on top 10.0 × 10.0 cm and a pyramidal part 0.2L long)	9914.4 (54)	145.5	8367.2	1.18
PPP 2 (also, with a pyramidal part of 0.4 L length)	11016.0 (60)	145.4	9263.8	1.20
PPP 3 (also, with a pyramidal part of 0.6 L length)	12301.2 (67)	145.0	9494.69	1.29
PPS 4 (also, with a pyramidal part 0.8 L long)	14320.8 (78)	145.0	10267.3	1.40
Control piles:				
Prismatic pile with section dimensions 6.7 × 6.7 cm	8996.4 (49)	145.2	6592.83	1.36
Prismatic pile with section dimensions 10.0 × 10.0 cm	15606.0 (85)	145.0	14666.6	1.06
Pyramidal pile with cross-sectional dimensions in the upper part 10.0 × 10.0 cm, in the lower part 6.7 × 6.7 cm	16891.2 (92)	145.0	9947.8	1.70

Note: L - length of piles without tip

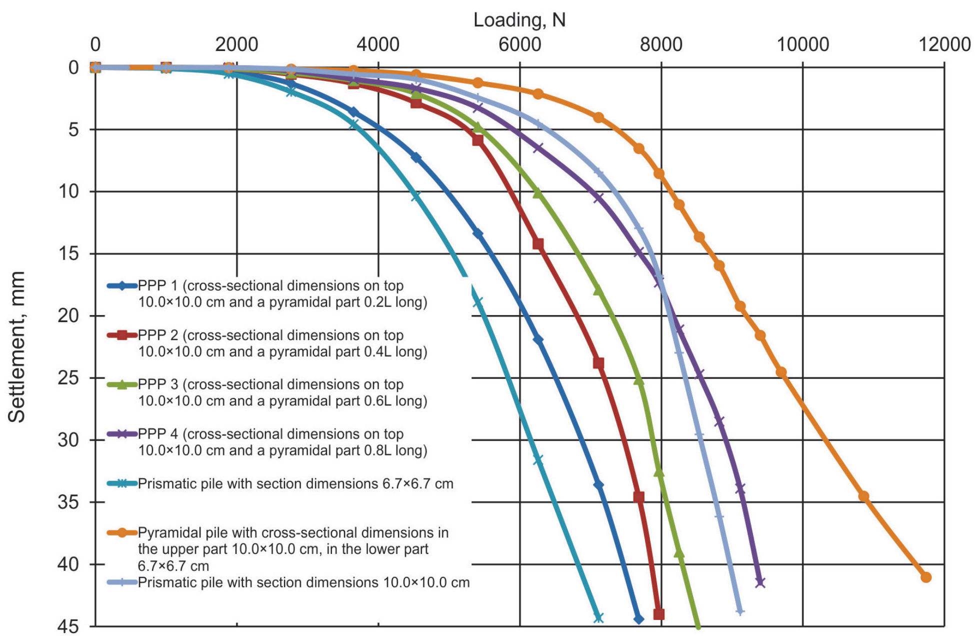


Fig. 3 Pile driving records

Table 4 Coefficient values of the relative energy consumption of driving K_e of pile models

Coefficients of relative power consumption of plugging	Coefficient values for experimental models of piles with the length of the pyramidal section			
	0,2 L	0,4 L	0,6 L	0,8 L
K_{e1}	1.10	1.24	1.37	1.60
K_{e2}	0.63	0.70	0.79	0.92
K_{e3}	0.58	0.65	0.73	0.85

Note: Coefficients, K_{e1}, K_{e2} and K_{e3} respectively refer to models of a prismatic pile with a cross-sectional area of 6.7 × 6.7 cm, a prismatic pile with a cross-sectional area of 10.0 × 10.0 cm and a pyramidal pile with a cross-sectional area of 10.0 × 10.0 cm above and below - 6.7 × 6.7 cm

The research results allow us to highlight the following features of the process of driving test piles:

- depending on the length of the pyramidal part of the PPP, with the same immersion depth, the experimental piles compared to prismatic and pyramidal piles can have both large (1.10–1.60 times) and smaller (8.0–37.0 %) energy consumption for driving;
- energy consumption for immersion of 1 m^3 of PPP is 1.03–1.32 times more and 5.43–44.07 % less than for prismatic and pyramidal piles;
- with an increase in the length of the pyramidal part of the PPP, the energy costs for driving them to the same depth increase by 1.16–1.44 times.

The results of field tests of piles are presents under the action of a vertical static load in Tables 5–7. Graphs of the dependence of the settlement of pile models on the vertical load are shown in Fig. 4.

A comparative assessment of the resistance of pile models to the action of an indentation load was carried out on the basis of the following indicators:

- bearing capacity F_d, determined by the formula, taking into account the requirements of SP RK 5.01-103-2013 "Pile foundations" (Table 5):

$$F_d = \gamma_c \frac{F_{u,n}}{\gamma_g}, \quad (1)$$

where: γ_c – the coefficient of pile working conditions, taken equal to 1,0; $F_{u,n}$ – the standard value of the ultimate resistance of the pile, taken equal to its smallest ultimate resistance according to the test results; γ_g – the soil safety factor, taken equal to 1,0.

- the characteristic value of the soil resistance to compression in the ultimate state in terms of bearing capacity $R_{c,k}$, determined by the formula in accordance with the requirements of SP RK EN 1997-1:2004/2011 [16]:

$$R_{c;k} = \frac{(R_{c;m})_{\min}}{\xi_2}, \quad (2)$$

where: $(R_{c;m})_{\min}$ – the smallest value of the measured value of the soil compressive resistance depending on the number of tests of pile models; ξ_2 – a correction factor for evaluating the results of testing pile models with a static load, taken equal to 1.40 (for $n = 1$); n is the number of tests of pile models;

- specific bearing capacity F_d^v, taken as the ratio of the bearing capacity of the pile to the volume of its submerged part in the ground (Table 5);
- the coefficient of the relative efficiency of the pile model in terms of bearing capacity K_H (by the characteristic value of soil compression resistance K_x), taken in the form of the ratio of the bearing capacity (characteristic value of the soil compressive resistance) of the experimental pile model to the similar force parameter of the control pile model.

The results of static tests of piles make it possible to establish the following features of the operation of experimental piles (at the same settlements):

- in comparison with a prismatic pile with a cross-sectional area of 6.7 × 6.7 cm, PPP have a higher bearing capacity (1.09–1.48 times);
- in comparison with a prismatic pile with a cross-sectional size of 10.0 × 10.0 cm, PPP with a pyramidal section length of 0.2 L–0.6 L have less (by 8.0–25.0 %), and PPP with a pyramidal section length 0.8 L – greater (1.04 times) bearing capacity;
- compared to a pyramidal pile (with dimensions at the top 10.0 × 10.0 cm and at the bottom – 6.7 × 6.7 cm), PPP have a lower (by 20.0–36.0 %) bearing capacity;

Table 5 Bearing values F_d and specific bearing capacity F_d^v piles, as well as the characteristic value of the soil compression resistance $R_{c,k}$

Pile type	Pile bearing capacity F_d, N, at settlement		Specific bearing capacity of the pile F_d^v, N/cm^3, at settlement		Characteristic value of soil compression resistance $R_{c,k}$, N, at settlement	
	20 mm	40 mm	20 mm	40 mm	20 mm	40 mm
Experienced piles:	6100	7470	0.73	0.89	4357.14	5335.71
PPP 1 (with cross-sectional dimensions on top 10.0 × 10.0 cm and a pyramidal part 0.2L long)						
PPP 2 (also, with a pyramidal part of 0.4 L length)	6820	7860	0.74	0.85	4871.43	5614.28
PPP 3 (also, with a pyramidal part of 0.6 L length)	7310	8300	0.77	0.87	5221.43	5928.57
PPP 4 (also, pyramidal part 0.8 L long)	8175	9340	0.80	0.91	5839.28	6671.48
Control piles:	5500	6825	0.83	1.03	3928.57	4875.0
prismatic with section dimensions 6.7 × 6.7 cm						
prismatic pile with section dimensions 10.0 × 10.0 cm	8125	8975	0.55	0.61	5803.57	6410.71
pyramidal pile with the dimensions of the upper section 10.0 × 10.0 cm and the lower section - 6.7 × 6.7 cm	9250	11625	0.99	1.17	6607.14	8303.57

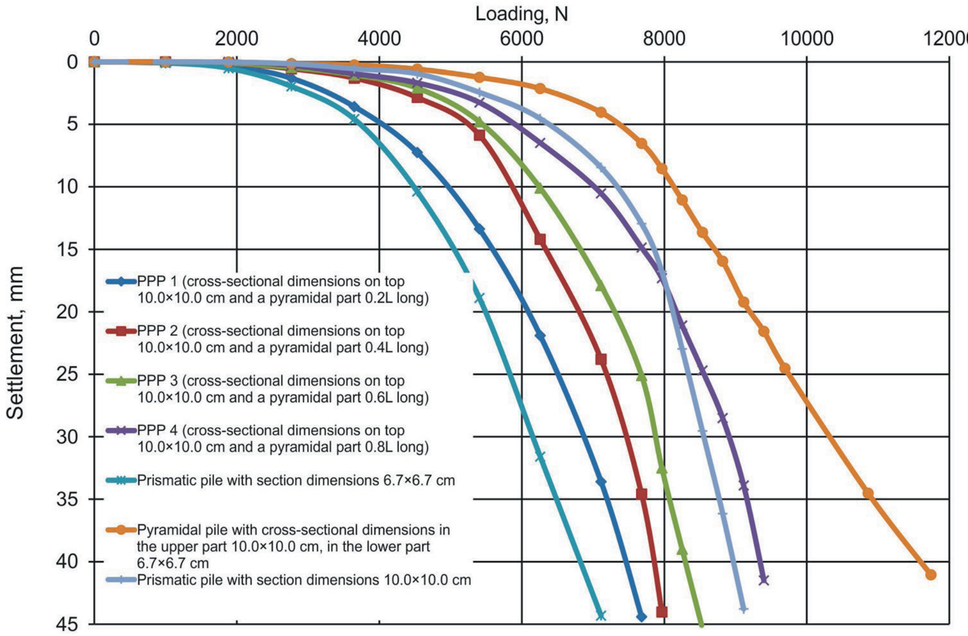


Fig. 4 Dependence of the pile settlement on the pressing static load

Table 6 Coefficient values of the relative efficiency of pile models for bearing capacity K_H at pile settlement to 20 mm

Relative efficiency coefficients for bearing capacity of models	Coefficient values for experimental models of piles with the length of the pyramidal part			
	0.2 L	0.4 L	0.6 L	0.8 L
K_{H1}	1.11	1.24	1.32	1.48
K_{H2}	0,75	0.84	0.90	1.0
K_{H3}	0.66	0.74	0.79	0.88

Note - Coefficients, K_{H1}, K_{H2} and K_{H3} respectively refer to models of a prismatic pile with a cross-sectional area of 6.7 × 6.7 cm, a prismatic pile with a cross-sectional area of 10.0 × 10.0 cm and a pyramidal pile with a cross-sectional area of 10.0 × 10.0 cm above and below 6.7 × 6.7 cm.

Table 7 Coefficient values of the relative efficiency of pile models for bearing capacity K_H at pile settlement to 40 mm

Relative efficiency coefficients for bearing capacity of models	Coefficient values for experimental models of piles with the length of the pyramidal part			
	0.2 L	0.4 L	0.6 L	0.8 L
K_{H1}	1.09	1.15	1.21	1.37
K_{H2}	0.83	0.87	0.92	1.04
K_{H3}	0.64	0.67	0.71	0.80

Note – Coefficients K_{H1}, K_{H2} and K_{H3} respectively refer to models of a prismatic pile with a cross-sectional area of 6.7 × 6.7 cm, a prismatic pile with a cross-sectional area of 10.0 × 10.0 cm and a pyramidal pile with a cross-sectional area of 10.0 × 10.0 cm above and below 6.7 × 6.7 cm

- the specific bearing capacity of the test piles is higher than the specific bearing capacity of a prismatic pile with a section size of 10.0 × 10.0 cm: with a pile settlement of 20 mm – 1.33–1.45 times; with precipitation of 40 mm – 1.46–1.49 times;
- with an increase in the length of the pyramidal part, the bearing capacity of the test piles (at the same settlement values) increases by 1.12–1.34 times.

Pile foundations, actually, operate under conditions of combined action of horizontal (moment) and vertical loads [17, 18]. Therefore, the study of the PPP on the horizontal load is urgent purpose.

The results of testing piles for horizontal loading performed in the field are presented in Tables 8 and 9, as well as in Fig. 5.

Comparative assessment of the resistance of piles to the action of horizontal (transverse) load was carried out on the basis of the coefficient of relative efficiency of pile models in horizontal displacement K_{gp} (transverse load resistance K_{tr}).

Coefficient $K_{gp}(K_{tr})$ is set as the bearing capacity ratio $F_{d.gp}$ (lateral load resistance R_{tr}) an experimental model of a pile (with a horizontal movement of 10 mm of its head) to a similar force parameter of the control model of a pile.

From Tables 8 and 9, the following patterns of behavior of experimental piles under the action of a horizontal load are follow:

- the bearing capacity of the PPP is 1.17–1.80 times greater than the bearing capacity of a prismatic pile with a section size of 6.7 × 6.7 cm;

Table 8 Bearing values $F_{d.gp}$ and lateral load resistance R_{tr} piles with horizontal displacement of their head by 10 mm

Pile type	Pile bearing capacity $F_{d.gp}$ (pile lateral load resistance R_{tr}), N
Experienced piles:	
PPP 1 (with cross-sectional dimensions on top 10.0 × 10.0 cm and a pyramidal part 0.2 L long)	2255
PPP 2 (also, with a pyramidal part of 0.4 L length)	2580
PPP 3 (also, with a pyramidal part of 0.6 L length)	2835
PPP 4 (also, with a pyramidal part 0.8 L long)	3450
Control piles:	
prismatic (with cross-sectional dimensions 6.7 × 6.7 cm)	1918
prismatic (with section dimensions 10.0 × 10.0 cm)	4310
pyramidal (with dimensions of the upper section 10.0 × 10.0 cm, the lower section 6.7 × 6.7 cm)	4030

- the bearing capacity of the PPP is 20.0–48.0 % less than the bearing capacity of a prismatic pile with a section size of 10.0 × 10.0 cm;
- the bearing capacity of the PPP is 15.0–44.0 % less than the bearing capacity of the pyramidal pile (with the dimensions of the upper section 10.0 × 10.0 cm and the lower section 6.7 × 6.7 cm);

Table 9 The values of the coefficients of the relative efficiency of experimental piles for horizontal displacement K_{gp1} (transverse load resistance K_{tr1})

Relative efficiency ratios	Coefficient values for experimental models of piles with the length of the pyramidal part			
	0.2 L	0.4 L	0.6 L	0.8 L
$K_{gp1}(K_{tr1})$	1.17	1.35	1.48	1.80
$K_{gp2}(K_{tr2})$	0.52	0.60	0.65	0.80
$K_{gp3}(K_{tr3})$	0.56	0.64	0.70	0.85

Note: $K_{gp1}(K_{tr1})$, $K_{gp2}(K_{tr2})$ and $K_{gp3}(K_{tr3})$ – coefficients related to the models of a prismatic pile with a cross-sectional area of 6.7 × 6.7 cm, a prismatic pile with a cross-sectional area of 10.0 × 10.0 cm and a pyramidal pile with a cross-sectional area of 10.0 × 10.0 cm, and to the bottom – 6.7 × 6.7 cm

- the bearing capacity of the test piles increases by 1.22–1.53 times with an increase in the length of the pyramidal part from 0.2 L to 0.8 L.

4 Calculation formulas

The data presented in Tables 6 and 7 are mathematically described by the following linear function:

$$K_H = al + b \,, \tag{3}$$

where: K_H - coefficient of relative efficiency for the bearing capacity of piles;

l – length of the pyramidal part of the PPP; a and b – coefficients taken according to Tables 10 and 11.

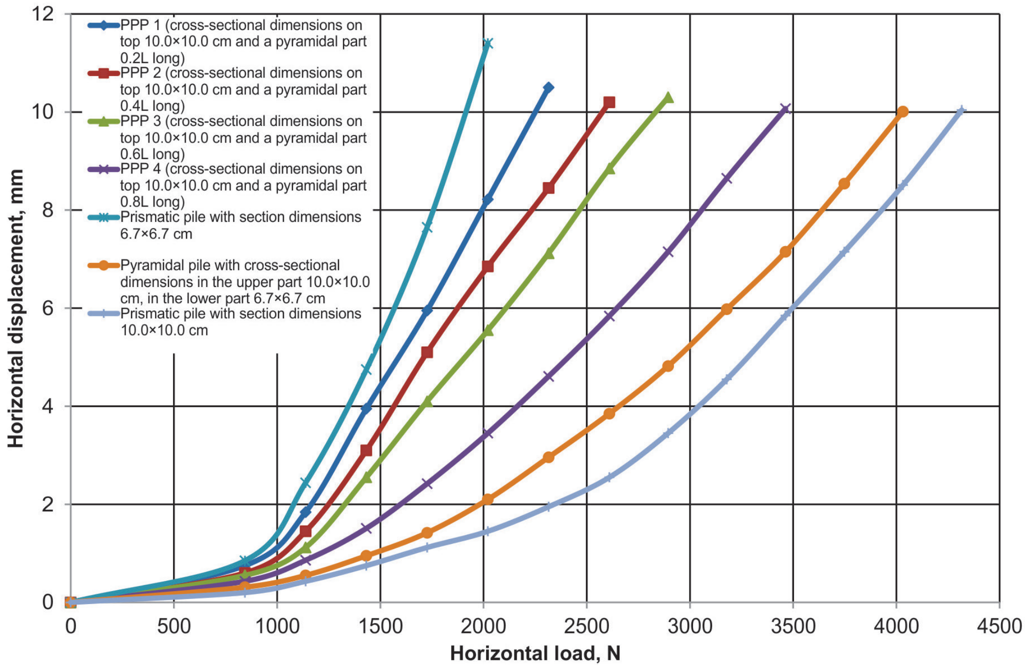


Fig. 5 Dependence of the displacement of the head of the piles on the static horizontal load

Table 10 Coefficient values of a and b in K_H Eq. (3) at pile settlement to 20 mm

Relative efficiency coefficients for bearing capacity of piles	Coefficient values a	Coefficient values b	The value of the accuracy of the approximation (R^2)
K_{H1}	0.119	0.99	0.985
K_{H2}	0.081	0.67	0.991
K_{H3}	0.071	0.59	0.989

Table 11 Coefficient values of a and b in K_H Eq. (3) at pile settlement to 40 mm

Relative efficiency coefficients for bearing capacity of piles	Coefficient values a	Coefficient values b	The value of the accuracy of the approximation (R^2)
K_{H1}	0.09	0.98	0.931
K_{H2}	0.068	0.745	0.928
K_{H3}	0.052	0.575	0.932

The data presented in Table 9 are mathematically describes by the following linear function:

$$K_{gp} = kl + p \ , \tag{4}$$

where: l - length of the pyramidal section of the PPP; k and p- coefficients taken according to Table 12.

The test results presented in Table 9 allow obtaining the following correlation dependences:

$$F_{\text{PPP}} = F_{gp1} + \Delta_F \ , \tag{5}$$

$$F_{\text{PPP}} = F_{gp2} - \Delta_F \ , \tag{6}$$

$$F \quad = F_{gp3} - \Delta_F \ , \tag{7}$$

$$\Delta_F = gl + d \ , \tag{8}$$

where: F_{gp1}, F_{gp2}, F_{gp3} - bearing capacity, respectively, of the model of a prismatic pile with a cross-sectional area of 6.7 × 6.7 mm, a model of a prismatic pile with a cross-sectional area of 10 × 10 mm and a model of a pyramidal pile with a cross-sectional size in the upper part of 10 × 10 mm, in the lower part – downward -6.7 × 6.7 mm, N; Δ_F – difference between the values of the bearing capacity of the test and control piles, N; g and d - coefficients taken from the Table 13; l – the length of the pyramidal section of the PPP.

The presented data allow us to draw the following conclusions:

- a calculation formula has been obtained that allows one to determine the experimental data of the relative efficiency coefficients for the bearing capacity of the PPP under the action of a pressing static load;

Table 12 The values of the coefficients k and p in the Eq. (4)

Horizontal relative efficiency ratios	Coefficient values k	Coefficient values p	The value of the accuracy of the approximation (R^2)
K_{gp1}	0.202	0.945	0.963
K_{gp2}	0.093	0.455	0.959
K_{gp3}	0.089	0.42	0.950

Table 13 The values of the coefficients g and d in the formula (8)

The quantity Δ_F in the formula	Coefficient values g	Coefficient values d	The value of the accuracy of the approximation (R^2)
(5)	384	98	0.960
(6)	-384	2210	0.960
(7)	-384	2490	0.960

- formulas are proposed for the calculated determination of the bearing capacity of the PPP under the action of a horizontal static load relative to a similar power parameter of the control piles;
- the obtained formulas are distinguished by a fairly high (from 92 to 99 %) reliability of the calculation results.

5 Conclusions

The following main conclusions can be formulated, based on the presented results of experimental studies:

- with an increase in the length of the pyramidal section of the PPP, the energy costs for their immersion increase, and their bearing capacity (specific bearing capacity) also increases under the action of pressing and transverse loads;
- depending on the length of the pyramidal section the PPP, in comparison with prismatic and pyramidal piles, have both greater and lesser bearing capacity (specific bearing capacity);
- for the calculated determination of the bearing capacity of the PPP under the action of a horizontal load, formulas were obtained that ensure high reliability of the calculation results.

Thus, the length of the pyramidal part of the PPP has a significant effect on the energy consumption of their driving, immersion and resistance to the action of an indentation and horizontal load, which it is explained, in our opinion, by effective compaction and a significant manifestation of soil repulsive forces under the inclined edges of the pyramidal part of the PPP when they are introduced into the soil strata.

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