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Research paper

Experimental research of pile toe resistance in natural conditions

Zygmunt Meyer[1], Paweł Siemaszko[2], Krzysztof Żarkiewicz[3]

Abstract: The model presented in this paper was prepared to determine the pile toe resistance mobilization mechanism. Due to the fact, that skin resistance of piles was widely analyzed by the Authors in previous papers [1,2] which were based on both field and laboratory test results, currently the main focus is to describe the mobilization of pile toe resistance. The physical experimental model consists of a chamber measuring 2.2 m, 2.4 m and 6.0 m in width, length, and height, respectively, filled with cohesionless soil. The model has a hydraulic cylinder to apply force at the pile head and equipment to measure pile settlement with force mobilized at the pile base. The purpose of this research was to verify previously formulated methods referring to the M–K curves. Furthermore, the research allowed us to examine if the relationship between pile toe resistance and force applied at the pile head is linear. As a result of the tests, it was confirmed that for purposes of practical engineering calculations, the resistance of the pile toe can be described regarding the load, which is applied at the pile head. The description of this relationship is presented with M–K curve parameters.

Keywords: pile, pile toe resistance, settlement, static pile load test

[1] Prof., DSc., PhD., Eng., West Pomeranian University of Technology, Faculty of Civil and Environmental Engineering, Szczecin, al. Piastów 50a, 71-311 Szczecin, Poland, e-mail: zygmunt.meyer@zut.edu.pl, ORCID: 0000-0002-2459-6262

[2] PhD., Eng., West Pomeranian University of Technology, Faculty of Civil and Environmental Engineering, Szczecin, al. Piastów 50a, 71-311 Szczecin, Poland, e-mail: pawel.siemaszko@siemaszko.pl, ORCID: 0000-0002-9944-4407

[3] PhD., Eng., West Pomeranian University of Technology, Faculty of Civil and Environmental Engineering, Szczecin, al. Piastów 50a, 71-311 Szczecin, Poland, e-mail: krzysztof.zarkiewicz@zut.edu.pl, ORCID: 0000-0003-0084-2569

1. Introduction

Pile skin resistance and toe resistance, in both field and laboratory conditions, are still a matter of research in many studies [3–6]. These studies' aim was to the determination of mechanisms of skin and toe resistance mobilization, with pile settlement based on the load, type of pile, pile shaft roughness, and soil conditions. Piles can be loaded horizontally and vertically, and the pile-soil interaction in both cases is still the subject of current research [7, 8] but in the scope of the presented paper only vertically loaded piles were analyzed. It appeared to be crucial to present the outcomes in the form of the load-settlement curve [9–12]. One of the methods, allowing the description of pile load-settlement relationship as a continuous curve, was developed initially by Meyer and Kowalow, later in the paper described as M–K curve [13]. The M–K pile settlement curve is presented as (1.1).

$$s = C_2 N_{\mathrm{gr},2} \frac{\left(1 - \dfrac{N_2}{N_{\mathrm{gr},2}}\right)^{-\kappa_2} - 1}{\kappa_2} \tag{1.1}$$

where: $N_{\mathrm{gr},2}$ – maximum load applied at the pile head causing uncontrolled settlement; vertical asymptote to the settlement curve [kN]; C_2 – diagonal asymptote at the beginning of settlement curve and reverse of Winkler constant coefficient [mm/kN]; κ_2 – dimensionless parameter describing the relationship between skin and toe resistance of the pile.

M–K settlement curve is determined using mathematical statistics, based on results of static pile load test set $\{N_i; s_i\}$. In this method parameters C_2, $N_{2,gr}$, κ_2 hat meet the conditions (1.2) are obtained using least squares method with requirement (1.2).

$$\delta = \sum \left(s_{i,m} - s_{i,c}\right)^2 = \text{minimum} \tag{1.2}$$

where: $s_{i,m}$ – measured settlement refers to the i-stage of pile load $N_{2,i}$; $s_{i,c}$ – calculated settlement refers to the i-stage of pile load $N_{2,i}$; $N_{2,i}$ – value of the load put at the head of the pile [kN].

An example of a pile settlement curve, obtained from M–K method based on measurements from static pile load test $\{N_i; s_i\}$ is presented in Fig. 1.

Table 1 presents the results of the static pile load test. There were 11 stages of load with intervals 100 kN. At every i-stage of N_2 load, stabilized pile head settlement s_i was recorded and presented in Table 1.

Table 1. Static pile load test results

$\boldsymbol{N_{2,i}}$	**[kN]**	0	100	200	300	400	500	600	700	800	900	1000	1100
$\boldsymbol{s_i}$	**[mm]**	0	0.51	1.02	1.61	2.34	3.22	4.23	6.05	7.68	10.38	15.03	19.96

Numerical and analytical research developed in the Department of Geotechnical Engineering of West Pomeranian University of Technology in Szczecin [2, 9, 14] allow determining M–K curve parameters for static pile load test results. There are also many analyses that applied M–K curve to investigate pile-soil interaction.

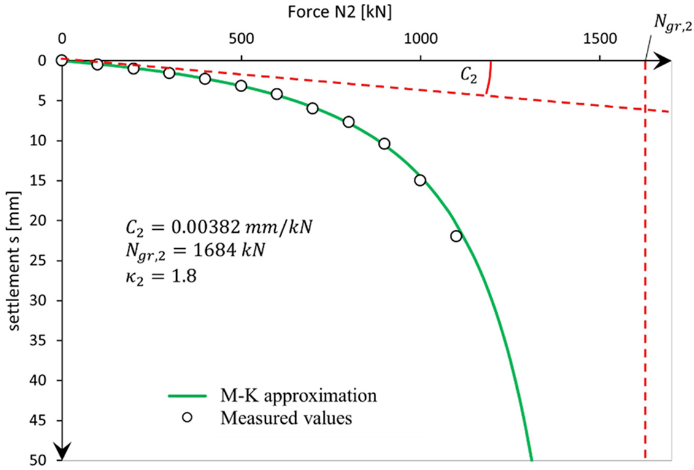

Fig. 1. M–K settlement curve as the interpretation of static pile load test

The latest research indicates that toe resistance is the division of load applied at the pile head and that division value does not depend (or depends slightly) on the actual settlement progression. The research that has been undertaken, aims to investigate if it is possible to confirm this assumption and to what extent it can be used in engineering practice.

2. Experimental research

The purpose of the experimental research was to conduct static pile load test with additional instrumentation, which allows to measure toe resistance. Static load tests were carried out in the prepared natural field model, which geometry allowed obtaining similar circumstances to natural piles used in practice, with accuracy close to laboratory conditions. The research stand consists of a rectangular chamber presented in Fig. 2. with 2.2 m, 2.4 m and 6.0 m in width, length, and height, respectively.

The model is constructed on a reinforced concrete foundation, which measures $300 \times 300 \times 50$ cm (length, width, depth), and consists of a formwork system with one of the wooden shells replaced with transparent plexiglass. The formwork is attached to the concrete foundation using steel rebars. The wall cover was prepared using transparent plexiglass with a thickness 15 mm. The transparency allowed to control of pile-soil behavior and static pile load test conditions, such as soil deformations and pile loading imperfections. The chamber was filled with cohesionless soil compacted layer by layer. A reinforced concrete pile with 0.4 m diameter and 3.0 m length was installed in the chamber. To achieve the natural roughness of pile skin, the pile has been previously made in-situ in displacement technology. The photographs of the field stand, and pile is presented on Fig. 3.

Static pile load tests were carried out with respects of Polish Code PN-83/B-02482 [15]. Axial load was applied on the pile head in stages. In every stage, the static load was maintained

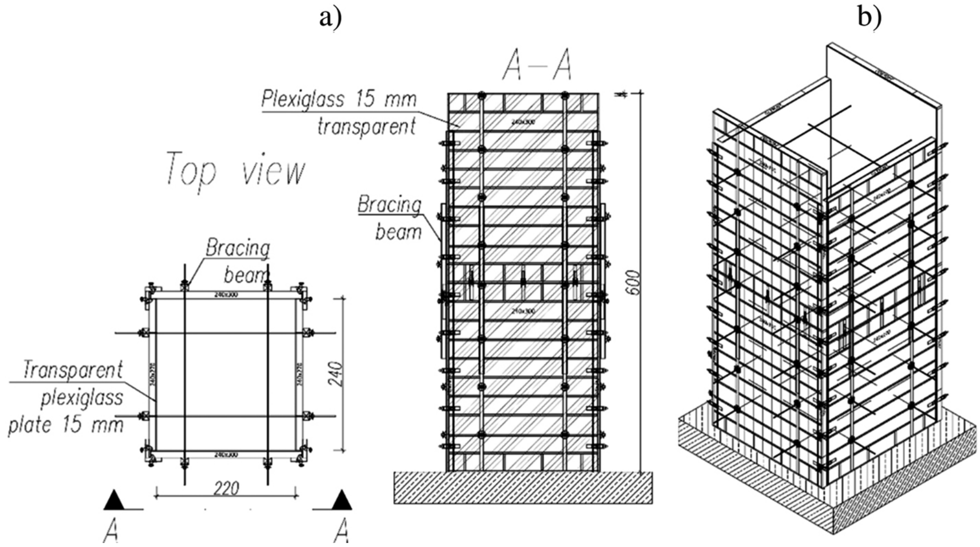

Fig. 2. Field research stand for pile load test. Dimensions of the chamber; a) Top view and cross section; b) 3D model of the chamber

a) b)

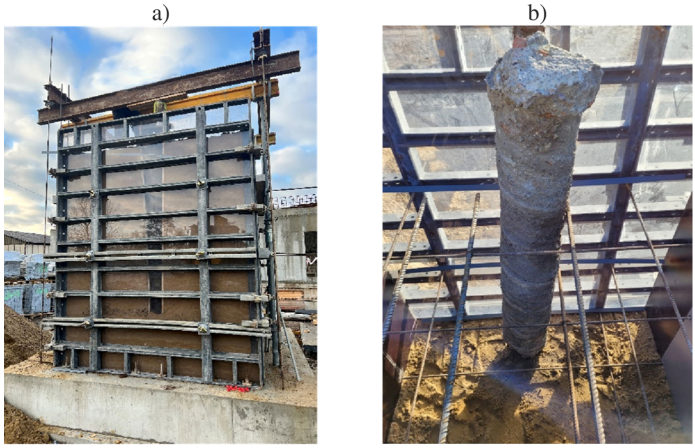

Fig. 3. Photographs of field research stand for a pile load test; a) Transparent chamber filled with soil, b) pile used in the investigations

to achieve settlement stabilization. In each stage, static load and stabilized settlement were measured. Outcomes of all stages provided the data $\{N_i; s_i\}$. Additionally, for every stage, the pile toe resistance was measured to achieve additional data $\{N_i; s_i\}$. Additionally, for every stage, the pile toe resistance was me. Pile toe resistance was measured using a special sensor allowing to measure stress at the pile toe level.

The flexible pressure sensors used in the study consist of two polymer layers separated by a stress-sensitive semiconductor. The dimensions of the sensor are 425×425 mm and the thickness is only 0.381 mm. The sensor has 1936 measurement points called sensel, distributed with a density of 1.1 sensel per 1 cm^2. The high density of measurement points made it possible to determine the redistribution and areas of stress concentration under the pile base. Measurement is carried out with a frequency of 1 Hz, which allows to capture, how resistance of the pile toe changes during the stabilization of pile settlement. Furthermore, the flexibility of the pressure map allowed to avoid the negative influence of the sensor on real soil behavior. The photographs of the sensor with the recorder are shown in Fig. 4.

a) b)

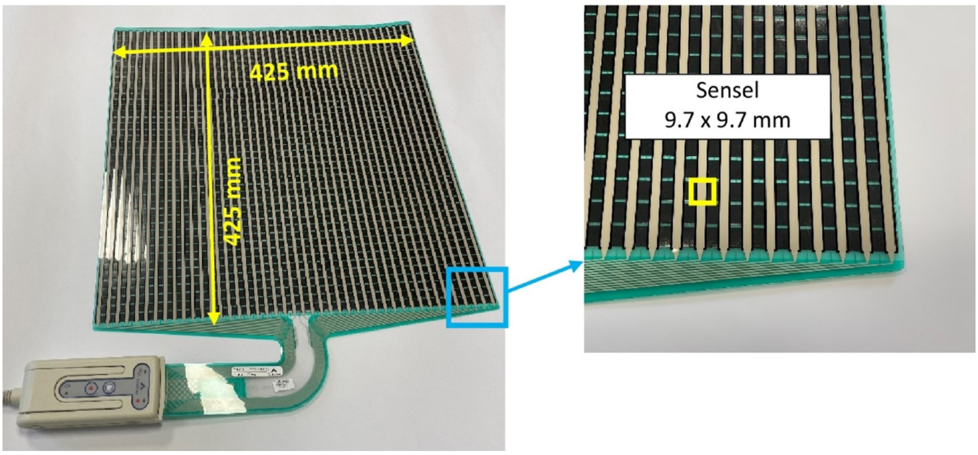

Fig. 4. Flexible pressure map used in measurements of pile toe resistance; a) Dimensions of pressure map, b) zoom on sensel

3. Results

The experimental investigation of pile toe resistance mobilization with the settlement, allowed to conduct the significant analysis of N_2 and N_1 relationship. The analysis allows to determine mechanisms of pile toe resistance mobilization based solely on static pile load test, without additional measurements. The results of the static pile load test are presented in Tables 2–4.

Initial experimental research, which is presented in the paper, confirms that for practical calculations the assumption in the form of Eq. (3.1) can be used.

$$N_1 = \text{const} \cdot N_2 \tag{3.1}$$

The relationship between pile toe resistance versus axial load applied at the pile head is Fig. 5. Linear equations presented in Fig. 5. were obtained using the least squares method.

Table 2. Static pile load test outcomes of pile PT1

PT1	***s* [mm]**	1.06	1.41	1.81	2.19	2.68	3.12	3.62	4.11	4.66	5.13	5.60	6.07	6.52
	N_2 [kN]	20.00	25.00	30.00	35.00	40.00	45.00	50.00	55.00	60.00	65.00	70.00	75.00	80.00
	N_1 [kN]	6.20	7.68	9.38	11.32	13.30	15.38	17.54	19.81	22.26	24.52	26.78	28.94	31.18

Table 3. Static pile load test outcomes of pile PT2

PT2	***s* [mm]**	0.93	1.79	2.88	4.08	5.49	6.99	8.49
	N_2 [kN]	19.96	29.98	39.93	49.93	59.92	69.82	80.00
	N_1 [kN]	7.92	11.34	15.30	19.63	24.24	29.11	33.47

Table 4. Static pile load test outcomes of pile PT3

PT3	***s* [mm]**	3.44	4.01	4.59	5.26	5.72	6.44	6.94	7.54	8.79	9.25	10.32
	N_2 [kN]	19.93	25.00	29.92	34.85	40.04	44.91	49.85	54.94	64.76	69.90	79.75
	N_1 [kN]	9.70	12.00	14.38	17.09	19.98	22.99	25.81	29.00	35.42	38.85	44.73

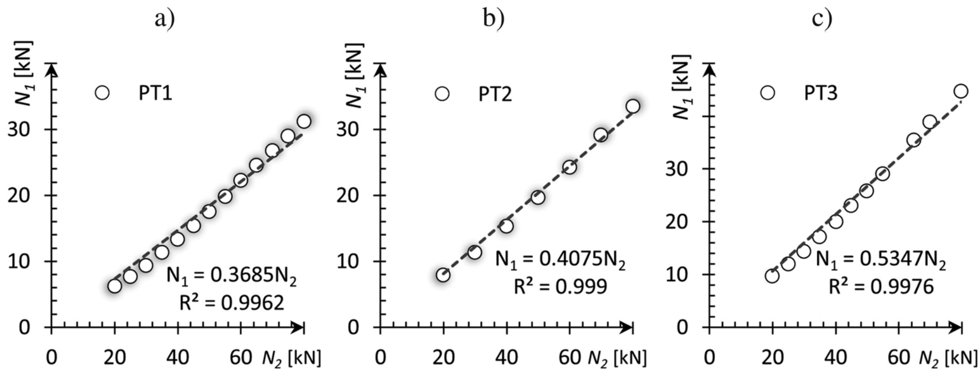

Fig. 5. Toe resistance versus axial load applied at the pile head with linear approximation; a) Pile PT1, b) pile PT2, c) pile PT3

4. Analysis of experimental results

The results of the pile load test were analyzed according to the M–K method to determine parameters that describe the load-settlement relationship: $N_{gr,2}$, C_2, κ_2. The approximation M–K curve can be also applied to the toe resistance versus settlement analysis. In this approach the M–K parameters take subscript 1 as follows: $N_{gr,1}$, C_1, κ_1. The analysis was carried out with the following assumptions:

1. The settlement curve is described by the M–K curve (4.1):

$$N_2 = N_2(s) = N_{gr,2}\left[1-\left(1+\frac{\kappa_2 s}{C_2 N_{gr,2}}\right)^{-\frac{1}{\kappa_2}}\right] \tag{4.1}$$

2. The toe resistance curve is described by the M–K curve (4.2):

$$N_1 = N_1(s) = N_{gr,1}\left[1-\left(1+\frac{\kappa_1 s}{C_1 N_{gr,1}}\right)^{-\frac{1}{\kappa_1}}\right] \tag{4.2}$$

3. And skin resistance curve from force balance equation:

$$T(s) = N_2(s) - N_1(s) \tag{4.3}$$

The scheme of toe resistance and skin resistance mobilization with the settlement as the division of settlement curve using M–K method is presented in Fig. 6.

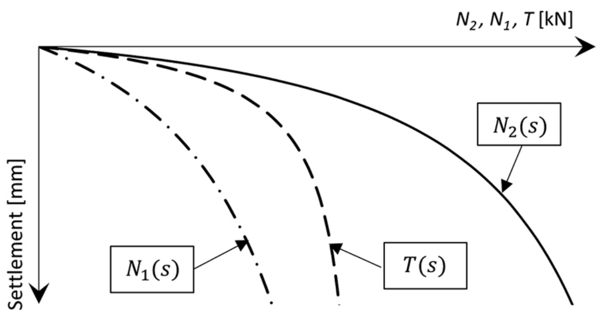

Fig. 6. The scheme of M–K settlement curve division on toe and skin resistance curves

Numerical investigations allowed to determine the relationship between the settlement curve and pile toe resistance curve in M–K method. The most accurate correlation was obtained for the following relationships (4.4–4.6) [16].

$$\kappa_1 = \ln(1+\kappa_2) \tag{4.4}$$

$$C_1 = C_2(1+\kappa_2)^2 \tag{4.5}$$

$$N_{gr,1} = \frac{N_{gr,2}}{2^{\kappa_2}} \tag{4.6}$$

For analytical calculation of toe resistance changes the following approach was applied (4.7).

$$N_1 = N_2 \cdot F(\kappa_1, \kappa_2) \tag{4.7}$$

The function F was determined using the division of the settlement curve on toe and skin resistances. To examine this assumption the parameters $N_{gr,2}$, C_2, κ_2 were approximated according to Chapter 1. The values of κ_1 were taken according to the previous research [16] from Eq. (4.4).

This approach allows to application a relation for the constant value from Eq. (4.7) (division) and κ_2. The most accurate correlation was achieved when the following formula (4.8) was applied.

$$N_1 = \frac{N_2}{(1+\kappa_2)^n} \tag{4.8}$$

And base on the statistical analysis the (4.9) was obtained.

$$n = \frac{\kappa_2}{\kappa_1} \tag{4.9}$$

Based on the presented approach the parameters of M–K model can be determined as they are presented in Table. 5.

Table 5. M–K parameters determined for piles PT1, PT2 and PT3

Pile	$F = 1/(1+\kappa_2)^n$	κ_2	κ_1
PT1	0.3685	0.83	0.61
PT2	0.4075	0.90	0.64
PT3	0.5347	0.63	0.49

Presented research is the initial step to approach the problem, which is having not enough elements in numerical calculations and mathematical statistics. It is needed to proceed with more experimental research in the field for different sorts of piles. It will be a matter of further research.

An attempt was made to take data from the two investigated piles and to verify if the assumed way of calculation $N_1(s)$, and $T(s)$ can be done with sufficient accuracy for practical calculations. The results of this approach are given in the Figs. 7 and 8.

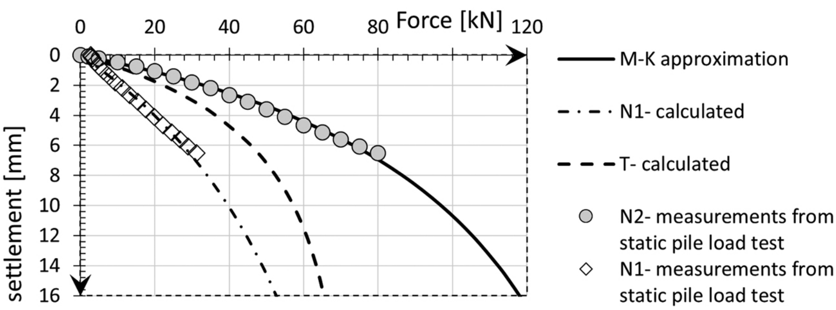

Fig. 7. Toe and skin resistances mobilization with settlement of pile PT1

The first attempt seems to give satisfactory results. Experimental investigation of pile toe resistance mobilization with settlement allowed to make the significant analysis of N_2 and N_1 relationship. The analysis allows to determine the mechanisms of pile toe resistance mobilization.

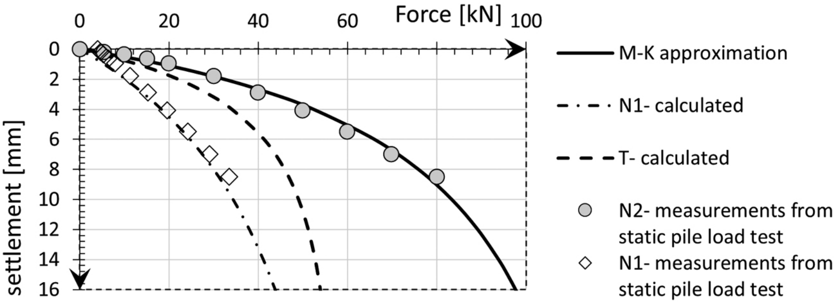

Fig. 8. Toe and skin resistances mobilization with settlement of pile PT2

5. Conclusions

The pile design process consists of calculations of skin and toe resistance for specific geotechnical circumstances. In practice, pile load capacity and corresponding settlement are usually verified in the field, with the use of a static pile load test. Static load test remains to be the crucial tool, due to the nature of pile-soil interaction, which is the closest static load test to actual building exploitation conditions. Even though the test itself provides only the data of ultimate bearing capacity referred to settlement of the pile head. In many cases, it is hard to verify whether the pile skin and toe resistance had been calculated properly or if the method of calculation requires any improvements.

The most accurate investigation is based on the static load test on instrumented piles, which can provide additional information about pile skin and toe resistance. This information may be directly used to verify the design approach. Nevertheless, that kind of pile investigation is not common in engineering practice, due to the significant effort required for test preparation and high costs.

The method of toe resistance determination, after verification, can be used in pile load capacity verification or in case of pile dimension changing in the same soil conditions.

This paper presents an analysis of pile toe resistance mobilization in non-cohesive soils during a static pile load test. The results of the experimental tests in natural scale on 3 piles, verify whether the relationship between the load applied in the pile head and the resistance of the pile toe can be assumed as linear in practical engineering calculations. The obtained verification indicates, that for the purposes of practical calculations, it can be assumed that this ratio does not depend on the settlement value.

The authors intend to perform tests for piles made with various technologies. The schedule for further research also provides for an analysis of the impact of the density ratio of non-cohesive soil on the test results. The first test results also confirm that it is possible to present the test static load curve Q-s in the form of three curves: $N_2\,(s)$, $N_1\,(s)$, $T\,(s)$ using M–K method.

For the analytical calculations, the authors used the previously developed and published relationships (4.4–4.6) to determine the parameters of the pile toe resistance curve in the M–K method.

Next research should also include static pile load tests which were made in a layered soil.

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Badania eksperymentalne oporu podstawy pala w warunkach naturalnych

Słowa kluczowe: pal, opór podstawy pala, osiadanie, próbne obciążenie statyczne pala

Streszczenie:

Przedstawiony w artykule model został przygotowany w celu określenia mechanizmu mobilizacji oporu podstawy pala. Ze względu na to, że opór pobocznicy pala był szeroko analizowany przez Autorów we wcześniejszych pracach [1, 2], które opierały się zarówno na wynikach badań terenowych, jak i laboratoryjnych, obecnie główny nacisk kładzie się na opisanie mobilizacji oporu podstawy pala.

Fizyczny model doświadczalny składa się z komory o wymiarach w rzucie 2,2 m na 2,4 m i wysokości 6,0 m, wypełnionej gruntem niespoistym. Model posiada siłownik hydrauliczny do obciążenia głowicy pala oraz sprzęt do pomiaru osiadania pala odnoszącego się do zmobilizowanego oporu u podstawy pala. Celem badań była weryfikacja wcześniej sformułowanych metod odnoszących się do krzywych M–K. Ponadto badania pozwoliły sprawdzić, czy zależność między oporem podstawy pala, a siłą przyłożoną do głowicy pala jest liniowa. W wyniku przeprowadzonych badań potwierdzono, że dla celów praktycznych obliczeń inżynierskich nośność podstawy pala można uzależnić od obciążenia, które działa na głowicę pala. Opis tej zależności przedstawiono za pomocą parametrów krzywej M–K.

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