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Stručni članak

DESIGN OF FOUNDATIONS REHABILITATION OF FACULTY OF CHEMISTRY IN BELGRADE WITH ANALYSIS OF MEGA PILES' CAPACITY

Mirjana Vukićević, Miloš Marjanović, Veljko Pujević,
Nikola Obradović, Sanja Jocković

Građevinski fakultet Univerziteta u Beogradu, Bulevar kralja Aleksandra 73, Beograd, mirav@grf.bg.ac.rs

ABSTRACT
This paper describes the solution of the rehabilitation of the foundations of the building of the Faculty of Chemistry in Belgrade, which suffered damage as a result of differential settlements, which happened several times during the exploitation. It was determined that the cause of settlements was moisturing of loess soil due to periodic watter spilling from damaged water network. Rehabilitation is done by jacking of MEGA piles, which prevents the appearance of additional settlements. The rehabilitation was carried out in 2012-2013. In a second part of the paper, the evaluation of pile capacity prediction methods based on CPT test results is carried out by comparing with the measured pile jacking force.

KEY WORDS: foundations repair, jacked-in MEGA pile, pile capacity, CPT

REŠENJE SANACIJE TEMELJA HEMIJSKOG FAKULTETA U BEOGRADU SA ANALIZOM NOSIVOSTI MEGA ŠIPOVA

REZIME
U radu je opisano rešenje sanacije temeljne konstrukcije objekta Hemijskog fakulteta u Beogradu koji je pretrpeo oštećenja kao posledice nejednakih sleganja, koja su se dešavala nekoliko puta u toku eksploatacije objekta. Analizom uzroka je utvrđeno da su sleganja posledica dodatnog provlažavanja lesa usled periodičnog izlivanja vode iz havarisane vodovodne mreže. Rešenjem sanacije je predviđeno utiskivanje šipova MEGA tehnologijom, čime se sprečava pojava dodatnih sleganja konstrukcije. Sanacija je izvedena 2012-2013. godine. U drugom delu rada je izvršena ocena metoda za proračun nosivosti šipova prema rezultatima CPT opita na osnovu poređenja sa izmerenim silama utiskivanja MEGA šipova.

KLJUČNE REČI: sanacija temelja objekta, MEGA šip, nosivost šipova, CPT

INTRODUCTION

The building of the Faculty of Chemistry was built in the late 1950s. During the period 1974-2007, several sudden settlements of the building parts have occurred. The biggest consequences of differential settlements have happened in March 1974 and July 2007. The consequences were crack openings (from mm to cm wide), cracking of glass surfaces, separation and rotation of certain parts of the building, de-flattening of floors and settlements of the walls up to 25 cm. Deformations and damages jeopardized the functionality and load capacity of the building. The Faculty of Civil Engineering in Belgrade has done the project of rehabilitation of the foundations structure (FCE 2008). According to this project, rehabilitation was carried out in the period from October 2011-April 2013. Geodetic surveying made after the rehabilitation according to the monitoring program have shown that no additional settlements of the structure have not occurred.

Figure 1. Building of Faculty of Chemistry in Belgrade

STRUCTURE OF THE BUILDING AND GEOTECHNICAL CONDICTIONS

The Faculty building (Fig. 1) consists of six blocks with different number of floors (two to six). The building structure is skeletal system on shallow foundations, mostly spread footings connected with beams.

The building is located on the slope towards the Danube, so the parts of the building are founded at different depths and in different geotechnical conditions. Geotechnical profile consists of embankment of heterogeneous composition, 1.5-5 m deep, loess up to the 8-11 m depth (collapsible above the groundwater level), and the marl clay below. The groundwater level oscillates between 5-6 m below the ground surface. Certain quantities of water drain from time to time into the soil from damaged water and sewage network, which affects the increase in the moisture of the surface layers of loess in the vicinity. Under these conditions, loess as collapsible soil suddenly loses its strength and increases deformability. Uncontrolled infiltration of water into the soil below the foundation caused the soil moisturing and the additional settlements of a certain number of foundations, resulting in the aforementioned deformations and damage to the building.

FOUNDATION REPAIR SOLUTION

When the solution for the foundation repair was chosen, degree of vulnerability of the building, the cause of the occurrence of settlements, as well as the technical conditions for performing the rehabilitation are taken into account. One of the most effective and technically feasible ways to prevent additional settlements is to support the object onto deeper, undamaged soil layers using MEGA piles that are jacked into the ground below the existing foundation structure. Because of the heavy load that is transferred from the building to the soil, piles of square cross section of 0.4x0.4 m, made of reinforced concrete elements with maximum jacking force of 1800 kN were selected. The required number of piles is obtained from the condition that, in the case of loess layer wetting and collapse, the entire load is transferred to the piles. A total of 270 piles were constructed. They are jacked in under existing spread footings and beams, and, where needed, additional beams were constructed between the adjacent footings and the piles were jacked in under them.

EVALUATION OF METHODS BASED ON CPT TEST RESULTS FOR PREDICTION OF MEGA PILES' CAPACITY

One of the advantages of using the MEGA piles is the possibility to control their bearing capacity during construction. By measuring the jacking force during pile installation, the pile is "tested" and the ultimate bearing capacity is obtained.

During the project design phase, ten CPT tests were executed, so it was possible to make an assessment of the pile bearing capacities based on the CPT test results for the piles close to the performed CPT tests. Total of 16 piles close to the performed CPT tests were selected for evaluation. Lengths of selected piles were ranging 6.25-9.85 m. Recorded jacking forces (Q_m) were in range 932-1765 kN. Soil profile (Table 1) was defined based on the results of CPT tests, as well as laboratory testing results of borehole samples (Kosovoprojekt 1974).

Table 1. Soil parameters

Soil layer	Water table (m)	Depth	Unit weight (kN/m^3)	USCS	Cohesion (kPa)	Frict. angle (°)	q_c (MPa)
Silty clay	6.5	0-2.5	19.0	CL	10	21	0.5-2.0
Silty clay / loess		2.5-6.5	19.0		20	22	2.0-3.0
		6.5-9.5	21.0		26	25	3.0-9.0
Stiff clay		9.5-11.5	21.0	CI/CH	30	27	2.0-14.5
Stiff marble clay		11.5+	21.0	CH	45	20	5.5-17.0

PILE CAPACITY PREDICTION METHODS

Two groups of methods are used in engineering practice for estimation of axial pile capacity. First group includes total stress (α-method) and effective stress analysis (β-method). In these methods, soil parameters for fine grained soils are obtained from lab tests, while parameters for coarse grained soils are usually correlated from results of in-situ tests. Second group of methods is directly based on the results of in-situ tests, mostly CPT (and CPTu), SPT and recently the DMT.

Table 2. Summary of direct CPT methods used for prediction of ultimate pile capacity

Method	q_b	q_s
Bustamante & Gianeselli (LCPC)	$q_b = k_{b1} q_{ca}$ q_{ca} - average q_c of zone ranging from 1.5D below the pile tip to 1.5D above the pile tip k_{b1}=0.15-0.60 - bearing factor depending on the soil and pile type and q_c value	$q_s = \frac{1}{\alpha_1} q_c \le q_{s,\max}$ α_1=30-200 - coefficient depending on soil type, pile type and value of q_c $q_{s,max}$ - maximum value of unit shaft friction depending on soil and pile type and q_c value
Schmertmann	$q_b = C_1 q_{ca} \le 15MPa$ q_{ca} - average q_c of zone ranging from 8D above the pile tip to 0.7D or 4D below the pile tip C_1=0.5-1.0 - coefficient depending on OCR	$q_s = k_{f1} f_s \le 120kPa$ k_{f1}=0.20-1.25 - coefficient for clay depending on pile material and sleeve friction
Tumay & Fakhroo	Similar to Schmertmann	$q_s = k_{f2} f_s \le 72kPa$ $k_{f2} = 0.5 + 9.5e^{-90 f_s}$ f_s in MPa
Penpile	$q_b = C_2 q_c \le 15MPa$ C_2=0.25 for pile tip in clay C_2=0.125 for pile tip in sand	$q_s = \frac{f_s}{1.5 + 14.47 f_s} \le 120kPa$ q_s and f_s in MPa
Philipponnat	$q_b = C_3 q_c \le 15MPa$ C_3 - coefficient depending on soil type (0.40 for sand, 0.45 for silt, 0.50 for clay)	$q_s = q_c \frac{\alpha_3}{F_{s1}} \le 120kPa$ α_3=0.30-1.25 - coeff. depending on pile type (1.25 for driven piles) F_{s1}=50-200 (50 for clay)
Aoki & De Alencar	$q_b = \frac{q_c}{F_b} \le 15MPa$ F_b=1.75-3.50 - coeff. depending on pile type	$q_s = q_c \frac{\alpha_5}{F_{s2}} \le 120kPa$ α_5=1.4-6% - coeff. depending on soil type F_{s2}=3.5-7 - coeff. depending on pile type

Note: D - pile diameter, q_c - cone tip resistance, f_s - sleeve friction.

Compared to other in-situ tests, CPT has the advantages based on its simplicity, speed and costs, continuous data record and possibilities for installation of additional sensors. CPT methods are based on hypothesis that the penetrometer represents a micro pile. These methods are empirical, formulated by comparison of CPT results with measured pile capacities in various soil conditions. In order to evaluate the methods' acceptability, as well as to improve them, it is important to always update the database of load test results for different soil conditions and pile types. In this paper, six direct CPT methods for predicting the ultimate capacity of MEGA piles were evaluated: Bustamante & Gianeselli (LCPC)

1982, Schmertmann 1978, Tumay & Fakhroo 1982, Penpile (Clisby et al. 1978), Philipponnat 1980 and Aoki & De Alencar 1975 (Table 2).

Measured load capacities (Q_m) for MEGA piles were obtained as final measured force during jacking (jacking of each pile is, in fact, a load test). The ultimate axial capacity (Q) is sum of pile base (Q_b) and shaft (Q_s) capacities:

$$Q = Q_b + Q_s = q_b A_b + \sum_{i=1}^{n} q_{s,i} A_{s,i} \tag{1}$$

where $q_{s,i}$ is the unit skin friction of the soil layer i, $A_{s,i}$ is pile shaft area interfacing with layer i, and n is the number of soil layers along pile shaft.

RESULTS OF STATISTICAL ANALYSIS

In order to evaluate the accuracy of prediction methods, statistical methods were used by many authors (Briaud & Tucker 1988, Eslami & Fellenius 1997, Abu-Farsakh & Titi 2004, Long & Wysockey 1999, Cai et al. 2009). The most illustrative parameter for method's accuracy is the Q_p/Q_m ratio, which can range from 0 to unlimited upper value, with an optimum value of 1. In this paper, prediction methods were evaluated using equations of best fit lines between measured and predicted pile capacity (Q_p/Q_m ratio) with corresponding coefficient of determination R^2. Trend lines of the Q_p/Q_m ratios for all evaluated methods are given in Fig. 2. Perfect fit line is plotted as dashed red line.

All evaluated methods show relatively high coefficient of determination R^2 (0.74-0.80). Presented results show that the Bustamante & Gianeselli (LCPC) method provides the best match between measured and estimated pile load capacities - Q_{fit}/Q_m ratio is close to one (0.986). Penpile method underpredicts the measured values for about 28% (Q_{fit}/Q_m=0.724). Other methods significantly overestimate the pile load capacities (28-63%).

DISCUSSION

The correlation factors for the current CPT methods are calibrated using limited amount of load test data. It is also common to most of the methods to impose limitations in terms of the maximum unit resistance of the base and the shaft, which many later studies have shown as unjustified approach. For most methods, the choice of correlation factors is not precisely defined, which increases the uncertainty of the methods. All of these factors affect predicting the pile capacity depending on the type of piles and soil.

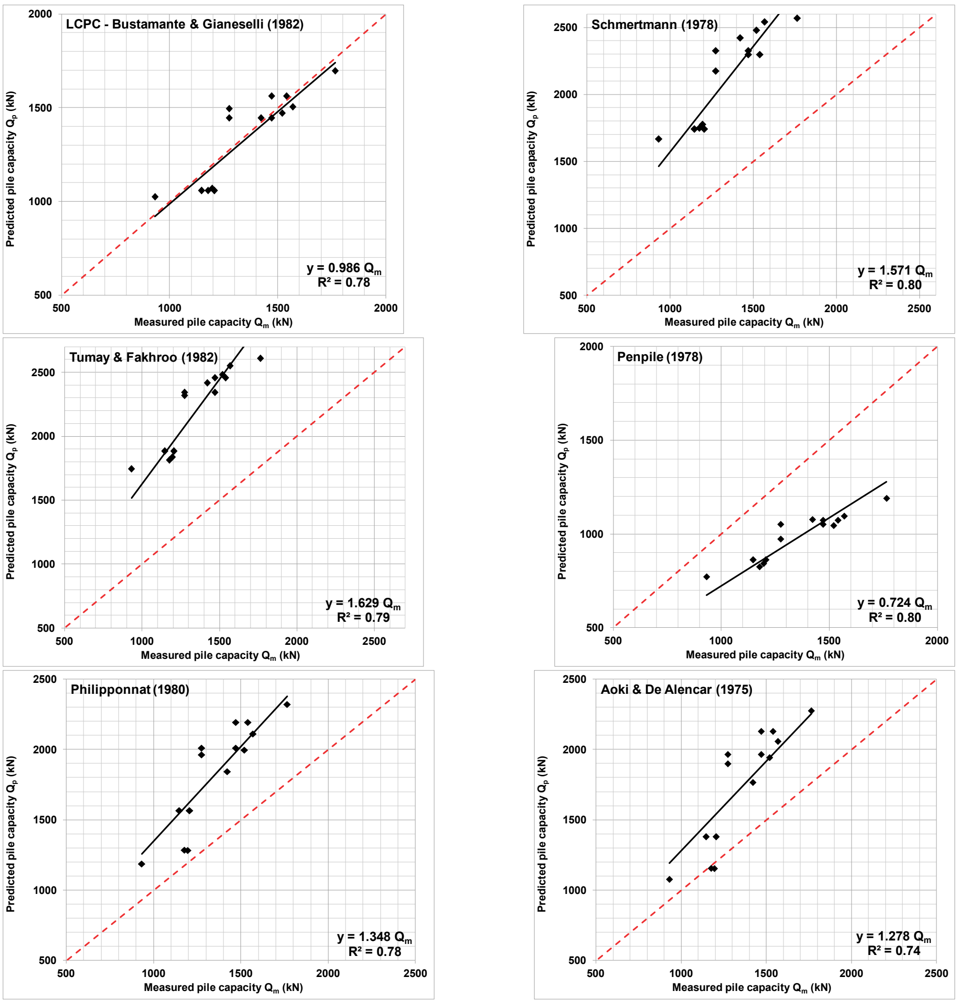

Figure 2. Predicted vs. measured ultimate pile capacity (Q_p/Q_m)

Bustamante & Gianeselli (LCPC) method is found to be the most appropriate method for prediction of load capacities of MEGA piles in considered soil conditions. This method defines the correlation factors that depend on the soil and pile types and cone resistance values more precisely than others. Penpile method underpredicts the load capacity of the piles, which is in line with the results of other authors (Abu Farsakh & Titi 2004, Cai et al. 2009), who have also found that this method is conservative. Other prediction methods signify-cantly overestimate pile load capacities.

CONCLUSIONS

This paper presented the evaluation of six methods for predicting the ultimate bearing capacity of jacked-in MEGA piles based on the CPT results. Sixteen piles with different lengths we-re considered. The final jacking force was used as the measured capacity of MEGA piles.

Based on presented results of this study, several conclusions can be made:

- Main factors influencing the disagreement between predicted and measured pile load capacities are imperfections of CPT methods and interpretation of pile load test results.
- Bustamante & Gianeselli (LCPC) method remains the most appropriate method for considered soil and pile types, and can be recommended for use in routine engineering practice.
- Penpile method significantly underpredicts the load capacity of the piles, which makes it a very conservative method.
- Schmertmann and Tumay & Fakhroo methods significantly overpredict the axial pile capacity and they were not suitable for the considered geotechnical conditions.

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