DETERMINATION OF AXIAL BEARING CAPACITY OF MEGA PILES ACCORDING TO EUROCODE 7

Nikola Obradović [1]
Miloš Marjanović [2]
Veljko Pujević [3]
Mirjana Vukićević [4]

UDK: 624.154(497.11)
DOI: 10.14415/konferencijaGFS2021.16

Summary: *Short review of provisions of Eurocode 7 for determination of pile axial bearing capacity is given in this paper. Design guidelines and recommendations for determination of bearing capacity of jacked-in MEGA piles, according to pile installation technology and chosen design approach in National Annex for Eurocode 7 (Part 1) in Serbia are presented. A validation of proposed guidelines through comparison with previous concept of allowable pile force is presented on the example of the rehabilitation of the foundations of a residential building in Zemun, Serbia. Obtained results confirm the adequacy of chosen design approach and proposed guidelines for determination of bearing capacity of MEGA piles.*

Keywords: *Eurocode 7, MEGA pile, bearing capacity, foundation repair.*

1. INTRODUCTION

Eurocode 7 (EC7) is based on the concept of the limit states and characteristic values. The introduction of such concept in geotechnical design is a major change in the traditio-nal design philosophy, which was based on a principle of allowable stresses and global safety factor. Therefore, the methodologies of geotechnical and structural design are harmonized. Limit state design is based on the proof of the ultimate, serviceability and durability limit states (ULS, SLS, DLS), using the partial safety factors. Such approach is semi-probabilistic, where characteristic values of random variables are adjusted using partial safety factors to account for any discrepancy in the input data (actions and material properties), as well as in the engineering models. These factors are calibrated to provide the required level of structural reliability. The partial safety factors and design approach chosen in Serbian EC7 National Annex (NA) for the determination of axial bearing capacity of MEGA piles are presented and validated in this paper.

[1] Asist. Nikola Obradović, mast. inž. građ., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 567, e–mail: nobradovic@grf.bg.ac.rs
[2] Doc. dr Miloš Marjanović, mast. inž. građ., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 567, e–mail: mimarjanovic@grf.bg.ac.rs
[3] Asist. Veljko Pujević, dipl. građ. inž., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 567, e–mail: vpujevic@grf.bg.ac.rs
[4] Prof. dr Mirjana Vukićević, dipl. građ. inž., University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia, tel: +381 11 3218 568, e–mail: mirav@grf.bg.ac.rs

The MEGA pile is a prefabricated, jacked-in pile, consisting of short elements made of steel or concrete. These piles are often used as an alternative to classic underpinning in medium to soft soils. By measuring the jacking force during pile installation, the pile is "tested" and the ultimate bearing capacity is obtained (the pile jacking can be considered as a pile load test). First, the small pit is excavated below the existing foundation, in order to mount the hydraulic jack and the first pile segment. In order to transfer the jacking force to the pile, the rigid steel structure is usually designed.

2. DESIGN OF AXIALY LOADED PILES ACCORDING TO EC7

Three design approaches (DA) are given in EC7 for the verification of the ultimate limit states GEO and STR. GEO limit state stands for failure or excessive deformation of the ground, when the resistance is mainly provided through the strength of soil or rock. STR limit state stands for internal failure or excessive deformation of the structure or structural elements, in which the strength of structural material is significant in providing resistance [1]. Design approach 1 (DA1) provides reliability by applying different partial safety factors to two variables in two separate calculations (combinations 1 and 2), while in DA2 and DA3 these factors are applied simultaneously to two variables in a single calculation [2].
For the verification of ultimate limit state of axialy loaded piles, the following relation must be satisfied:

$$F_{c;d} \le R_{c;d} \tag{1}$$

where $F_{c;d}$ is design value of axial compression load on a pile or a group of piles, and $R_{c;d}$ is design value of compressive resistance of the ground against a pile, at the ULS.
Design value of axial compression load on a pile is given as:

$$F_{c;d} = \gamma_G G_{rep} + \gamma_Q Q_{rep} \tag{2}$$

where γ_G and γ_Q are partial safety factors for the permanent and variable actions, and G_{rep} and Q_{rep} are representative values of permanent and variable actions, respectively. Representative values of actions are calculated as a product of characteristic values of acti-ons and coefficients for combinations.
EC7 allows the determination of the pile compressive resistance $R_{c;d}$ at ULS using the results of static load tests, dynamic load tests, penetration tests (CPT and SPT), as well as the theoretical solutions of soil mechanics (e.g. c-φ method). The latter are treated as alternative methods by EC7.
Design value of compressive resistance of the ground against a pile at ULS is given as:

$$R_{c;d} = R_{b;d} + R_{s;d} = \frac{R_{b;k}}{\gamma_b} + \frac{R_{s;k}}{\gamma_s} = \frac{R_{c;k}}{\gamma_t} \tag{3}$$

where $R_{b;d}$, $R_{s;d}$ / $R_{b;k}$, $R_{s;k}$ are design/characteristic values of the pile base/shaft resistances, respectively. γ_b, γ_s and γ_t are partial safety factors for base, shaft and total pile resistance, and $R_{c;k}$ is characteristic value of total ground resistance against a pile (pile axial resistance). If alternative methods for determination of pile capacity are used, partial safety factors for pile resistance must be increased by model factor γ_{RM}, greater than 1 [3]. Characteristic value of pile axial resistance, determined using the results of static load tests, is defined as:

$$R_{c;k} = \min\left\{\frac{\left(R_{c;m}\right)_{mean}}{\xi_1}; \frac{\left(R_{c;m}\right)_{\min}}{\xi_2}\right\} \tag{4}$$

where $(R_{c;m})_{mean}$/$(R_{c;m})_{min}$ are average/minimum measured values of pile bearing capacities from static load test, and ξ_1/ξ_2 are correlation factors for evaluation of the results of static pile load tests (in terms of number of tested piles). Values of partial and correlation factors are given in Tables 1 and 2, according to the Serbian NA [4].

Table 1. Partial safety factors for different design approaches

Design approach	γ_G	γ_Q	γ_φ	$\gamma_{c'}$	γ_{cu}	γ_b (driven piles)	γ_s (driven piles)	γ_t (driven piles)
DA1 Comb. 1	1.35	1.5	1.0	1.0	1.0	1.0	1.0	1.0
DA1 Comb. 2	1.0	1.3	1.0	1.0	1.0	1.3	1.3	1.3
DA2	1.35	1.5	1.0	1.0	1.0	1.1	1.1	1.1
DA3	1.35 1.0*	1.5 1.3*	1.25	1.25	1.4	1.0	1.0	1.0

**Partial safety factors for geotechnical actions*

Table 2. Correlation factors for static pile load tests (n – number of tests)

n	1	2	3	4	≥5
ξ_1	1.4	1.3	1.2	1.1	1.0
ξ_2	1.4	1.2	1.05	1.0	1.0

According to the Serbian NA, DA2 should be used for the determination of axial pile capacity.

3. AXIAL CAPACITY OF MEGA PILES ACCORDING TO EC7

In order to calculate the axial capacity of MEGA piles, according to EC7, several assumptions must be established:

- Maximum MEGA pile jacking force ($F_{c,max}$) is considered as equal to the axial pile capacity at ULS,
- The process of MEGA pile jacking is considered as static load test [5].

Based on these assumptions, it can be assumed that the maximum jacking force $F_{c,max}$ is equal to pile capacity measured from static load test ($R_{c;m}$). Additionally, if a total number of MEGA piles used in a specific foundation project is larger than 5 (which is common case) and if all piles are jacked-in to the same jacking force, then both correlati-on factors ξ_1 and ξ_2 are equal to 1. Therefore, mean and minimum measured force from static load test are equal, and characteristic value of pile axial capacity is equal to the maximum pile jacking force:

$$\left.\begin{array}{l} R_{c;k} = \min\left\{\dfrac{\left(R_{c;m}\right)_{mean}}{\xi_1};\dfrac{\left(R_{c;m}\right)_{\min}}{\xi_2}\right\} = \min\left\{\left(R_{c;m}\right)_{mean};\left(R_{c;m}\right)_{\min}\right\} = R_{c;m} \\ R_{c;m} = F_{c,\max} \end{array}\right\} \rightarrow R_{c;k} = F_{c,\max} \quad (5)$$

From Eq. 3 and 5, the design pile capacity is:

$$R_{c;d} = \frac{R_{c;k}}{\gamma_t} = \frac{F_{c,\max}}{\gamma_t} \quad (6)$$

4. VALIDATION OF PROPOSED DESIGN APPROACH

Previous Serbian design guidelines [6] were based on the principle of allowable force in the pile. In the case of MEGA piles, maximum working force in the pile S_c must be smaller than allowed force in the pile $S_{c,allow}$, based on the following relation:

$$S_c \le S_{c,allow} = \frac{F_{c,\max}}{FS} \quad (7)$$

where FS is global safety factor for axial capacity of MEGA piles (usually equal to 1.5). In order to validate the proposed assumptions and design approach for the determination of axial capacity of MEGA piles using EC7, the "equivalent" safety factor based on EC7 is introduced and compared to previously used FS. Considering the simplest case, where only one variable load is acting on the pile, the representative values of actions are equal to characteristic values. Then the design and characteristic values of axial compression load on a pile are equal to:

$$\begin{array}{l} F_{c;d} = \gamma_G G_k + \gamma_Q Q_k \\ F_{c;k} = G_k + Q_k \end{array} \quad (8)$$

The ratio of permanent and variable loads contributing to characteristic value of total pile force $F_{c;k}$ can be denoted as α_G and α_Q (with $\alpha_G+\alpha_Q=1$):

$$\alpha_G = \frac{G_k}{F_{c;k}}$$
$$\alpha_Q = \frac{Q_k}{F_{c;k}} = 1 - \alpha_G \tag{9}$$

Combining Eq. 8 and 9, the design value of axial compression load on a pile is equal to:

$$F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = \gamma_G \alpha_G F_{c;k} + \gamma_Q \alpha_Q F_{c;k}$$
$$F_{c;d} = F_{c;k}\left(\gamma_G \alpha_G + \gamma_Q \alpha_Q\right) = F_{c;k}\left(\gamma_G \alpha_G + \gamma_Q\left(1-\alpha_G\right)\right) \tag{10}$$
$$F_{c;d} = \left(\gamma_G \alpha_G + \gamma_Q\left(1-\alpha_G\right)\right) F_{c;k}$$

If we assume that the maximum working force in the pile S_c is equal to characteristic value of total pile force $F_{c;k}$ (which is the assumption on the safe side), the relation between previously used FS and new partial safety factors from EC7 can be established. Combining Eq. 1, 6, 7 and 10, the following relation (at ULS) is obtained:

$$\left.\begin{aligned} S_c &\le \frac{F_{c,\max}}{FS} \\ F_{c;d} &\le R_{c;d} = \frac{F_{c,\max}}{\gamma_t} \end{aligned}\right\} \rightarrow FS = \frac{F_{c,\max}}{S_c} = \frac{R_{c;d}\gamma_t}{S_c}$$
$$F_{c;k} = S_c \rightarrow FS = \left(\gamma_G \alpha_G + \gamma_Q\left(1-\alpha_G\right)\right)\gamma_t \tag{11}$$
$$FS = \left(\gamma_G \alpha_G + \gamma_Q\left(1-\alpha_G\right)\right)\gamma_t$$

Possible range of α is between 0-1 (although the self-weight of pile is always present). Substituting the values of partial safety factors for DA2 (γ_t=1.1, γ_G=1.35, γ_Q=1.5) into Eq. 11 yields the following linear equation:

$$FS = 1.65\left(1 - 0.1\alpha_G\right) \tag{12}$$

The variation of FS with value of α for chosen DA2 is between 1.485-1.65, which is in line with previously used FS=1.5, in Serbia.

5. DESIGN EXAMPLE

Previously proposed design guidelines are illustrated on the project of the rehabilitation of foundations of a residential building in Zemun [7]. The building was built in 1965, with basement, ground floor and four floors. The building is 42 m long and 12.7 m wide. In

1990 additional floor was built. Original foundations were reinforced concrete strip footings. The vertical structural elements are massive brick walls. The soil profile consists mostly of loess sediments (up to 15 m).
In spring of 2019, the building suffered serious damage after accident on plumbing instalation near the building. Water inflitration to the loess caused the differential settlements of the building. A series of cracks and fissures appeared in building facade, basement walls and walls inside. Therefore, the building foundations had to be rehabilitated. For the rehabilitation of foundations, circular MEGA piles with outer diameter of 323 mm were adopted as remediation measure. Total design load to be caried by MEGA piles is 74690 kN, according to EC7. In total, 90 MEGA piles were designed, with the design load in one pile of 830 kN, according to EC7. Corresponding length of MEGA piles is about 10 m. Therefore, required total characteristic pile resistance is 913 kN, and proposed pile jacking force is 920 kN.
Maximum working (unfactored) pile force is 608 kN, based on static calculation, which yields the global safety factor (based on the principle of allowable force) of FS=920/608=1.51. Therefore, the proposed design rehabilitation design, based on EC7, meets the requirements of former Serbian design practice.

6. CONCLUSIONS

The procedure for the prediction of the axial capacity of piles according to EC7 is presented in this paper. The proposed design approach in Serbian NA is presented and validated for the prediction of capacity of MEGA piles. The presented validation is based on the following assumptions:

- Maximum MEGA pile jacking force is equal to the axial pile capacity at ULS,
- The process of MEGA pile jacking is considered as static load test,
- a total number of used MEGA piles in a foundation design is larger than 5,
- all piles are jacked-in to the same jacking force,
- the max. working force in the pile is equal to characteristic value of pile force.

If assumptions above are met (which is usual case), the proposed design approach in Serbian NA matches the global safety factor from previous design code, based on the principle of allowable stresses. This means that the proposed design approach in Serbian NA is appropriate for the design of jacked-in MEGA piles.

ACKNOWLEDGMENTS

This research was funded by Serbian Government, Ministry of Education, Science and Technological Development, via Project 200092.

REFERENCES

[1] SRPS EN 1997-1:2017 *Eurocode 7: Geotechnical design - Part 1: General rules*, Institute for standardization of Serbia, **2017**.
[2] Bond, A., Harris, A.: *Decoding Eurocode 7*, Taylor and Francis Group, **2008**.
[3] Obradović, N., Pujević, V., Vukićević, M.: A comparative analysis of pile design using Eurocode 7 and National Code of Practice (in Serbian), *Proceedings of 8th International Conference "Geotechnics in Civil Engineering"*, **2019**, p.p. 79-86.
[4] SRPS EN 1997-1/NA:2020 *Eurocode 7: Geotechnical design - Part 1: General rules - National Annex*, Institute for standardization of Serbia, **2020**.
[5] Vukićević, M., Marjanović, M., Pujević, V., Obradović, N.: Evaluation of methods for predicting axial capacity of jacked-in and driven piles in cohesive soils. *Građevinar*, **2018**, 70 (8), p.p. 685-693
[6] Pravilnik o tehničkim normativima za temeljenje građevinskih objekata (in Serbian), Sl. list SFRJ 15/90, **1990**.
[7] Projekat za izvođenje (PZI) sanacije temeljne konstrukcije objekta u Milana Uzelca br. 9-11 (in Serbian), Građevinski fakultet Univerziteta u Beogradu, **2020**.

ПРОРАЧУН АКСИЈАЛНЕ НОСИВОСТИ МЕГА ШИПОВА ПРЕМА ЕВРОКОДУ 7

Резиме: *У раду је приказан кратак преглед одредби Еврокода 7 за прорачун аксијалне носивости шипова. Дате су смернице и препоруке за прорачун аксијалне носивости утиснутих МЕГА шипова у складу са изабраним прорачунским приступом према националном прилогу за Еврокод 7 (Део 1) у Србији и специфичностима технологије извођења. Приказана је упоредна анализа прорачуна прогнозне носивости МЕГА шипова према Еврокоду 7 и ранијем Правилнику о техничким нормативима за темељење грађевинских објеката, заснованом на теорији допуштених напона, на примеру санације темеља стамбене зграде у Земуну. Добијени резултати потврђују адекватност изабраног прорачунског приступа у националном прилогу и предложених смерница за прорачун носивости МЕГА шипова.*

Кључне речи: *Еврокод 7, МЕГА шип, носивост шипова, санација темеља*