PROBABILISTIC ANALYSIS OF BEARING CAPACITY OF PILES WITH VARIABLE PARAMETERS IN CPT TEST AND CALCULATION ACCORDING TO THE REQUIREMENTS OF EUROCODE 7 (EN 1997-1: 2004) REGULATIONS

Abstract

A probabilistic concept for determining pile bearing capacity is presented, taking into account the variability of CPT test parameters and methodology of calculation according to the requirements of Eurocode 7 (EN 1997-1: 2004). Based on a single initial (real) CPT test, a larger number of generated (simulation) CPT tests are introduced drawn from solutions of statistics and probability theory. Research has found that the best solutions are achieved using the DA 2 design approach for n(CPT) ≥ 10 tests. Taking into account the deterministic and probabilistic approach in the analysis of pile bearing capacity, it is found that for the DA 2 design approach, the ratio of pile bearing capacity obtained from simulation and the capacity as determined through three methods (Mazurkiewicz, Van der Ven and hyperbolic approximation) is \( R_{c,d}/P_u \approx 1.148. \) Using the reliability index, the following values of partial resistance factors are obtained: \( \gamma_{h,b} \approx 1.1, \gamma_{s,b} \approx 1.1, \) which also points to the DA 2 design approach.

INTRODUCTION

Factors involved in determining and decision-making on the bearing capacity of piles are still burdened by a series of dilemmas, despite the sophisticated technology used when testing piles. The deterministic approach in identifying the bearing capacity of piles leaves the engineer-expert, as a final decision-maker, with a very limited space in the theory of decision making, given that one can only speak about the unique value of pile capacity. On the other hand, if the matter is discussed using the probability theory, then each individual value from the value spectrum has a specific probability of occurrence, with several of these values having the appropriate level of reliability. However, the key method in both of these approaches establishes a relation between the results of testing real pile models in real conditions (in-situ) with specific mathematical/engineering laws and standards for determining the pile bearing capacity. Thus, the generalization of the problem derived in real conditions and on a real pile model. The final result of the pile test, according to the SLT test, is a force-settlement curve, based on which the second stage determines the final value of the pile bearing capacity by using certain...
mathematical methods. The criteria and methods for determining pile bearing capacity, based on the solution obtained from SLT, have different mathematical formulations, which leads to different solutions. The most commonly used methods for determining the bearing capacity of piles based on SLT test are the following: Van der Veen's /1/, Mazurkiewicz's /2/, Decourt's /3/, Chin-Kondner's /4/ and the like. However, before initiation of the SLT test it is necessary to determine the value of the pile bearing capacity using analytical and/or numerical methods, which enables an adequate plan to be created in a timely manner for testing the bearing capacity of a real pile model. The procedure for implementing SLT is presented in detail in ASTM D 1143 /5/, which among other things provided a list of information that should be included in a test report. There is a well-established term in engineering terminology – 'prediction of pile bearing capacity', which refers to the procedure for determining pile bearing capacity before the implementation of the SLT test. This includes: methods based on the use of laboratory and in-situ experiments with correlations, methods using simplified theoretical solutions and analytical procedures, and methods based on improved analytical and numerical procedures, /6/. Empirical methods (the first group) are based on principles of soil mechanics which include: methods of correlation from the cone penetration test (CPT); methods of correlation from the standard penetration test (SPT); and variations of dynamic methods. Methods that use simplified theoretical solutions and analytical procedures (the second group) consider the soil model as linear-elastic, brittle-plastic and nonlinear material. Numerical analyses (the third group) are in most cases based on the finite element method (FEM), but the boundary element method (BEM) and the finite difference method (FDM) are also applied.

This research is based on a probabilistic concept of bearing capacity of piles by introducing parameter variability in the CPT test. Solutions obtained using this approach are compared with those obtained from the SLT test.

EXISTING PILE CAPACITY SOLUTIONS ACCORDING TO SLT, CPT AND PROBABILISTIC CONCEPTS

Pile capacity testing using a number of different CPT-based approaches is shown in /7/, while paper /8/ presents a new CPT-based pile capacity test procedure. New expressions for the analysis of pile bearing capacity have been proposed in /9/, establishing correlation between values obtained from SLT and CPT tests. On the other hand, the study /10/ uses regression analysis which, based on the results from tests conducted on a significant number of piles, predicts the bearing capacity of the piles and soils of different properties. The paper /11/ compares the pile bearing capacity as determined using the CPT test and the pile base bearing capacity as determined using the SLT test. The development of modern methods for predicting the bearing capacity of piles is based on the fact that the bearing capacity of piles of different properties and different types of soil that contain the piles can be determined using mathematical formulations for a specific set of pile and soil types. A research which is based on this approach by applying support vector machine (SVM) and CPT test results is presented in /12/, while paper /13/ presents the research that links the least square support vector machine (LSSVM) and artificial intelligence. Given the certain degree of variation, and in many circumstances a pronounced level of unreliability (uncertainty), of a number of parameters involved in determining the bearing capacity of piles, these parameters also need to be included in the analysis of bearing capacity. In this sense one can speak about the reliability of obtained solutions for the bearing capacity of piles. Studies analysing the reliability of solutions based on the unreliability of input parameters are shown in /14, 15, 16/, taking into account the n-σ criterion /17/ and including the Bayesian theory in /16/ and /18/. Analyses of reliability of applying different methods in determining the bearing capacity of piles are shown in /19, 20/.

SLT TEST AND DETERMINING THE PILE BEARING CAPACITY; CPT TEST

Verification of methodology of pile capacity analysis presented in this study is based on the SLT test of a real pile model in actual conditions. Testing a pile using SLT test against vertical pressure force is conducted for the facility of SILOSI in the framework of TE Kostolac ‘A’ in Serbia, /21/. Figure 1 shows the situation with the position of the considered pile Š35 and research works. In terms of construction technology, it is a reinforced bored pile of Dp = 1 m diameter and Lp = 14 m length. For the purposes of research presented here, the key test is the cone penetration test labelled CPT-1 IMS, conducted in the immediate vicinity of the tested pile.

Figure 2 shows the force-settlement curve (test load curve) for the considered pile Š35, determined using the SLT test (system of concrete blocks and hydraulic press). During the SLT test, a constant pressure force is maintained throughout the entire load phase, with the following parameters being measured: the force that acts on the pile; pile head settlement; and the time soil consolidation, /22/. The experiment was first carried out for the load level of 2900 kN, then with the new load increment up to 3250 kN a higher increment of settlement is realized than in the first case. Ultimate values of capacity of the pile Š35 are also determined based on analytical procedure, by extrapolating the obtained force-settlement curves according to the following methods: Mazurkiewicz’s (hyperbolic extrapolation) Pw = 3270 kN, Van der Veen’s (exponential extrapolation) Pw = 3252 kN and hyperbolic approximation Pw = 3831 kN. The arithmetic mean of the results obtained based on the above methods (Pw = 3451 kN) is adopted as the ultimate capacity of pile Š35 tested using SLT.

In addition to testing the pile using SLT, the soil is also tested by using CPT. Figure 3a shows the CPT test diagram, where qC is the soil resistance during the penetration of the cone, while qL is the total friction along the skin. Soil classification is carried out using Fuzzy methodology in the CPT-IT software, /23/ (Fig. 3b). The highest share (the highest likelihood of occurrence) is that of sandy soil (orange colour), while clay soil (clayey sand) is also present to some extent.
Probabilistic analysis of bearing capacity of piles with variable … Proba

Figure 1. Situation with the position of the tested pile Š35 and research works, /7/.

Figure 2. Force-settlement curve (test load curve) of the considered pile Š35, determined using the SLT test, /21/.
PROBABILISTIC ANALYSIS OF PILE BEARING CAPACITY

The parametric pile capacity analysis presented in this part of the paper is based on Eurocode 7 (EN 1997-1: 2004) /24/ requirements and probability theory. Starting from the initial CPT test (real CPT test), using statistical analyses and taking into account the variability of basic parameters of CPT test, a large number of CPT tests are generated (simulation CPT tests). Based on the results obtained from the initial (actual) CPT test, the total pile capacity $R_c$ is determined as the aggregate value of capacity in the pile base $R_b$ and pile skin $R_s$ /24/: 

$$R_c = R_b + R_s$$  (1)

Given the larger number of generated (simulation) CPT tests introduced in addition to the initial (actual) CPT test, Eq. (1) becomes:

$$R_{c,i} = R_{b,i} + R_{s,i}$$  (2)

where $R_{c,i}$ is the total pile bearing capacity obtained based on the results of i-th simulation CPT test; $R_{b,i}$ is the capacity in pile base obtained based on the results of the i-th simulation CPT test, and $R_{s,i}$ is the capacity in pile skin obtained based on the results of the i-th simulation CPT test. Values of pile bearing capacity are reduced by a factor $\gamma$, by which capacities can be further reduced as a function of the CPT test (statistical evaluation):

$$R_{c,cal,i} = R_{b,cal,i} + R_{s,cal,i} = \frac{R_{b,i}}{\gamma} + \frac{R_{s,i}}{\gamma}$$  (3)

The capacity in the pile base obtained from results of the i-th simulation CPT test $R_{b,i}$ is determined from:

$$R_{b,i} = A_b p_b$$  (4)

where $A_b$ is the area of pile base cross-section, while $p_b$:

$$p_b = 0.5 \alpha_p \beta s (\frac{q_{c,I,mean} + q_{c,II,mean} + q_{c,III,mean}}{2})$$  (5)

where $\alpha_p$ is the factor of pile class ($\alpha_p = 0.5$ bored pile); $\beta$ is the factor of pile base expansion ($\beta = 1$); $s$ is the factor of pile shape ($s = 1$); $q_{c,I,mean}$ is the mean value of $q_{c,I}$; $q_{c,II,mean}$ is the mean of the minimum value of cone resistance $q_{c,II}$; and $q_{c,III,mean}$ is the mean value of resistance $q_{c,III}$ according to Eurocode 7 (EN 1997-2: 2007), /25/: 

$$q_{c,I,mean} = \frac{1}{d_{cr}} \int_0^{d_{cr}} q_{c,I} dz$$
$$q_{c,II,mean} = \frac{1}{d_{cr}} \int_{d_{cr}}^{d_{ext}} q_{c,II} dz$$
$$q_{c,III,mean} = \frac{1}{8 D_{eq}} \int_0^{-8 D_{eq}} q_{c,III} dz$$  (6)

The capacity of pile skin $R_{s,i}$ is determined by:
where \( R_{f,k} = O_p \int_0^L p_i dz \) (7)

where \( O_p \) is the pile circumference, while:

\[ p_i = \alpha_i q_{c,z,a} \quad \text{(8)} \]

where \( \alpha_i \) is the friction factor along the pile skin; \( q_{c,z,a} \) is the ultimate value of \( q_{cat} \) (z) depth. The minimum and the mean value of total capacity of the pile are determined based on its total capacity calculated from the initial (actual) CPT test and generated (simulation) CPT tests. The minimum value of total capacity of the pile \( R_{c,k,\text{min}} \) obtained from all CPT tests is determined by:

\[ R_{c,k,\text{min}} = R_{b,k,\text{min}} + R_{s,k,\text{min}} \quad \text{(9)} \]

where:

\[ R_{b,k,\text{min}} = \min \left( \frac{R_{b,k,\text{cal,i}}}{\xi_4} \right), \quad R_{s,k,\text{min}} = \min \left( \frac{R_{s,k,\text{cal,i}}}{\xi_4} \right) \quad \text{(10)} \]

The mean value of total capacity of the pile \( R_{c,k,\text{mean}} \) obtained from all CPT tests is determined by:

\[ R_{c,k,\text{mean}} = R_{b,k,\text{mean}} + R_{s,k,\text{mean}} \quad \text{(11)} \]

where:

\[ R_{b,k,\text{mean}} = \frac{1}{N} \sum_{i=1}^{N} R_{b,k,\text{cal,i}}, \quad R_{s,k,\text{mean}} = \frac{1}{N} \sum_{i=1}^{N} R_{s,k,\text{cal,i}} \quad \text{(12)} \]

Correlation factors \( \xi_1 \) and \( \xi_2 \) depend on the calculation method used (CPT test) and the number of generated (simulation) CPT tests. Figure 4 shows the change in correlation factors \( \xi_1 \) and \( \xi_2 \) as a function of the number of (simulation) CPT tests generated, \( n(CPT) \).

Figure 4. Change in correlation factors \( \xi_1 \) and \( \xi_2 \) as a function of the number of generated (simulation) CPT tests \( n(CPT) \).

It is evident that correlation factors for \( n(CPT) \geq 10 \) become constant, while for a smaller number of CPT tests, values of these factors are considerably higher. The value of total bearing capacity of the pile from \( n(CPT) \) tests, \( R_c \), is determined as the minimum value of \( R_{c,k,\text{min}} \) and \( R_{c,k,\text{mean}} \):

\[ R_c = \min \left( R_{c,k,\text{min}}, R_{c,k,\text{mean}} \right) \quad \text{(13)} \]

The value of total bearing capacity of the pile from \( n(CPT) \) tests, \( R_{c,d} \), is reduced by the partial factors of pile base resistance \( \gamma_b \) and pile skin resistance \( \gamma_s \) as:

\[ R_{c,d} = \min \left( R_{c,d,\text{min}}, R_{c,d,\text{mean}} \right) \quad \text{(14)} \]

where:

\[ R_{c,d,\text{min}} = \frac{R_{b,k,\text{min}}}{\gamma_b} + \frac{R_{s,k,\text{min}}}{\gamma_s} \quad \text{(15)} \]

According to Eurocode 7 (EN 1997-1; 2004) /24/ requirements, three design approaches (DA) should be taken into account when determining the pile bearing capacity: DA 1; DA 2; and DA 3. Each design approach introduces different partial resistance factors for pile base and skin. Since the research presented here is based on the analysis of capacity of bored piles, the partial resistance factors for design approaches are as follows: \( \gamma_b = 1.25; \gamma_s = 1 \) (DA 1); \( \gamma_b = 1.1; \gamma_s = 1.1 \) (DA 2); and \( \gamma_b = 1; \gamma_s = 1 \) (DA 3).

The introduction of variability of parameters in the pile capacity analysis, according to the concept of probability theory, is conducted for input parameters obtained from the CPT test. Variation of the soil resistance parameter is considered during the penetration of the cone \( q_c(z) \) at a depth (z) through normal distribution (Gaussian distribution), whose probability density function (PDF), /26/, is:

\[ f\left[q_c(z)\right]g_{c,\text{mean}}(z), \sigma_c(z) = \frac{1}{\sigma_c(z) \sqrt{2\pi}} e^{-\frac{\left[q_c(z) - q_{c,\text{mean}}(z)\right]^2}{2\sigma_c(z)^2}} \quad \text{(16)} \]

where \( q_{c,\text{mean}}(z) \) is the mean value, and \( \sigma_c(z) \) is standard deviation. First the analyses for \( q_c(z) \) values are conducted based on normal distribution for the \([-\sigma_c(z),+\sigma_c(z)] \) interval and the 0.1[\( \sigma_c(z) \)] increment of standard deviation. The analysis is initiated by calculation of coefficient of variation \( C_v \):

\[ C_v = \frac{\sigma_c(z)}{q_{c,\text{mean}}(z)} \quad \text{(17)} \]

However, considering that the value of standard deviation \( \sigma_c(z) \) during the initiation of calculation is unknown, the coefficient of variation \( C_v \) is determined as a percentage value \( k \), so that standard deviation \( \sigma_c(z) \) is determined as:

\[ \sigma_c(z) = k q_{c,\text{mean}}(z) \quad \text{(18)} \]

The value of \( \sigma_c(z) \) at (z) depth is defined so to be equal to \( q_{c,\text{mean}}(z) \). In the next step, a set of \( n\sigma_c(z) \) values in the interval of \([-3\sigma_c(z),+3\sigma_c(z)] \) is determined for each (z) value, and then an appropriate set of \([q_c(z) - 3\sigma_c(z), q_c(z) + 3\sigma_c(z)] \) values. For each of these values, PDF functions are determined in the following interval:

\[ f\left[q_c(z)\right]g_{c,\text{mean}}(z), -3\sigma_c(z) \leq q_c(z) \leq +3\sigma_c(z) \leq \text{(19)} \]

Interval \([q_c(z) - 3\sigma_c(z), q_c(z) + 3\sigma_c(z)] \) is chosen given that, according to the normal distribution, the function of random variable (RND) in this interval yields with the following probability:

\[ P_{c_r}\left[q_{c,\text{mean}}(z) - 3\sigma_c(z) \leq q_c(z) \leq q_{c,\text{mean}}(z) + 3\sigma_c(z)\right] = 0.9973 \quad \text{(20)} \]
In the second step, using the function of random variable, simulation CPT tests are generated, obtaining thereby the simulated values of soil resistivity during the penetration of cone at \( z \) depth \( q_{c,\text{sim}}(z) \):

\[
q_{c,\text{mean}}(z) - 3\sigma_{c}(z) \leq RND(q_{c,\text{sim}}(z)) \leq q_{c,\text{mean}}(z) + 3\sigma_{c}(z)
\]

(21)

After that, based on Eq.(16), PDF functions of \( f[RND(q_{c,\text{sim}}(z))|q_{c,\text{mean}}(z),\sigma_{c}(z)] \) and discrete values of generated simulation \( RND(q_{c,\text{sim}}(z))|q_{c,\text{mean}}(z),\sigma_{c}(z) \) at \( z \) depth, where the abscissa shows normalized values of standard deviation \( n\sigma_{c}(z) \).

Figure 5 shows probability density functions of standard normal distribution of \( f[q_{c}(z)|q_{c,\text{mean}}(z),\sigma_{c}(z)] \) and discrete values of generated simulation \( RND(q_{c,\text{sim}}(z))|q_{c,\text{mean}}(z),\sigma_{c}(z) \) at \( z \) depth, where the abscissa shows normalized values of standard deviation \( n\sigma_{c}(z) \).

Figure 6 shows the diagrams of the original CPT test and generated CPT tests as a function of coefficient of variation \( C_{v} \). It is evident that by increasing the values of coefficient of variation \( C_{v} \), a wider interval of soil resistance values can be covered during cone penetration \( q_{c,\text{sim}}(z) \) along depth \( z \). Thus, the impact of variations in soil quality is taken into account for a given pile, or a given group of piles.

NUMERICAL ANALYSES OF PILE BEARING CAPACITY

Based on the methodology formulated in the previous section, numerical analyses of bearing capacity of the pile are conducted. The coefficient of variation is considered as percentage value \( C_{v} = (5\%, \ 10\%, \ 20\%, \ 30\%) \), so that a total of 80 CPT simulation tests are generated. Figure 5 shows probability density functions of standard normal distribution of \( f[q_{c}(z)|q_{c,\text{mean}}(z),\sigma_{c}(z)] \) and discrete values of generated simulation \( RND(q_{c,\text{sim}}(z))|q_{c,\text{mean}}(z),\sigma_{c}(z) \) at \( z \) depth, where the abscissa shows normalized values of standard deviation \( n\sigma_{c}(z) \).

Figure 6 shows the diagrams of the original CPT test and generated CPT tests as a function of coefficient of variation \( C_{v} \). It is evident that by increasing the values of coefficient of variation \( C_{v} \), a wider interval of soil resistance values can be covered during cone penetration \( q_{c,\text{sim}}(z) \) along depth \( z \). Thus, the impact of variations in soil quality is taken into account for a given pile, or a given group of piles.
The bearing capacity of the pile according to \( n(CPT) \) tests, \( R_{c,d} \), is normalized by the ultimate bearing capacity of the SLT-tested pile \( P_u \), shown in Fig. 7 as a function of design approaches DA 1, DA 2, and DA 3. In this way, changes in \( R_{c,d}/P_u \) can easily be monitored, so that when \( R_{c,d}/P_u < 1 \) it can be said that the capacity of the pile as determined by CPT test simulations is lower than the ultimate capacity based on SLT test. The best solution (determined by CPT test simulations is lower than the ultimate capacity based on SLT test. The best solution \((R_{c,d}/P_u = 1)\) is obtained for the second design approach DA 2 with partial resistance factors of \( \gamma_s = 1.1, \gamma_b = 1.1 \), and for \( n(CPT) \geq 10 \) tests. This clearly demonstrates the importance of conducting larger number of CPT tests or generating these based on the procedure described in the previous section.

For each design approach regression analysis is conducted using a third order polynomial (PReg):

\[
PRc_d/P_u = an(CPT)^3 + bn(CPT)^2 + cn(CPT) + d \quad (22)
\]

where high values for the coefficient of correlation \( r^2 \) are obtained. Values of coefficients \( a, b, c \) and \( d \) are presented in Table 1.

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<th>Table 1. Coefficients</th>
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<th>( c )</th>
<th>( d )</th>
<th>( r^2 )</th>
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Analogous to the calculation of PDF function for CPT test parameters, PDF functions for the \( R_{c,d}/P_u \) ratio are also calculated:

\[
f_{R_{c,d}/P_u}(R_{c,d}/P_u) = \frac{1}{\sigma_R \sqrt{2\pi}} \exp\left(-\frac{(R_{c,d}/P_u - \mu)^2}{2\sigma^2}\right) \quad (23)
\]

where \( (R_{c,d}/P_u)_{\text{mean}} \) is the mean value, and \( \sigma_R \) is standard deviation. Figure 8 shows the probability density functions of normal distribution \([R_{c,d}/P_u](R_{c,d}/P_u)_{\text{mean}} \sigma_R\) and the discrete values of normalized pile capacity \([R_{c,d}/P_u](R_{c,d}/P_u)_{\text{mean}} \sigma_R\) as a function of design approaches DA 1, DA 2 and DA 3. The deviation of calculated discrete values from the simulation is very small and it is almost located at the probability density function of normal distribution.

In order to determine the probability so that the calculated \( R_{c,d}/P_u \) ratio is lower than 1, the function of cumulative probability of normal distribution (CDF - cumulative distribution function) is determined according to /16/, with an additional adjustment for the purpose of this research:

\[
F_{R_{c,d}/P_u}(R_{c,d}/P_u) = P(R_{c,d}/P_u \leq 1) = \frac{1}{\sigma_R \sqrt{2\pi}} \int_{-\infty}^{R_{c,d}/P_u} \exp\left(-\frac{(R_{c,d}/P_u - \mu)^2}{2\sigma^2}\right) dR \quad (24)
\]

Figure 9 shows the cumulative probability function of normal distribution \( F(R_{c,d}/P_u)(R_{c,d}/P_u)_{\text{mean}} \sigma_R \) and discrete values of normalized pile capacity \( F(R_{c,d}/P_u)(R_{c,d}/P_u)_{\text{mean}} \sigma_R \) as a function of design approaches DA 1, DA 2 and DA 3. The calculated values of probability of \( P \) for \( R_{c,d}/P_u = 1 \), and the identified values of \( R_{c,d}/P_u \) for the probability of \( P = 1 \) across all design approaches (DA 1, DA 2, DA 3) and coefficients of variation \( C_v \) are shown in Table 2.

![Figure 7. Normalized pile capacity values \( R_{c,d}/P_u \) as a function of design approaches DA1, DA2 and DA3.](image-url)
When the pile capacity test is conducted for a known value of probability of $P = 1$, then the best solution is obtained for design approach DA 1 across all coefficients of variation $C_v$, whereby the mean value for $R_{c,d}/P_u$ is 1.085. When the pile capacity test is conducted for a known value of $R_{c,d}/P_u = 1$, then the best solution is also obtained for design approach DA 1 across all coefficients of variation $C_v$, whereby the mean value for $P$ is 0.99. However, this analysis shows that the necessary condition is fulfilled, but it is insufficient.

By combining design approach DA 2 as the optimum solution obtained based on the deterministic approach with the solution obtained based on the probability theory, the mean $R_{c,d}/P_u$ value for the known probability value of $P = 1$ is 1.147, while the mean value of probability $P$ for the known $R_{c,d}/P_u = 1$ is 0.62. This indicates a probability of $P = 0.62$ in the case when the ultimate capacity of the tested pile S35 is determined by using the arithmetic mean of the results of three methods (Mazurkiewicz, Van der Veen and...
Table 2. Calculated values of probability $P$ for $R_{c,d}/P=1$ and determined values of $R_{c,d}/P_{u} = 1$ for probability of $P=1$ across all design approaches (DA 1, DA 2 and DA 3) and variations of $C_r$.

<table>
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<th>$C_r$ (%)</th>
<th>DA</th>
<th>$P$ (known)</th>
<th>$R_{c,d}/P_{u}$</th>
<th>$P$ (known)</th>
<th>$R_{c,d}/P_{u}$</th>
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<tbody>
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Table 3 shows calculated values of reliability index $\beta$ across all design approaches (DA 1, DA 2 and DA 3) and coefficients of variation $C_r$ and the corresponding partial resistance factors $\gamma_b,\gamma_s$.

<table>
<thead>
<tr>
<th>$C_r$ (%)</th>
<th>DA</th>
<th>$\beta$</th>
<th>$\gamma_b$</th>
<th>$\gamma_s$</th>
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<td>1.097</td>
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<td>3</td>
<td>2.59</td>
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<tr>
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<td>1.063</td>
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The study found that the best solutions are achieved by applying the design approach DA 2 with partial resistance factors $\gamma_b=1.1$, $\gamma_s=1.1$, and for the number of simulation CPT tests $n(CPT) \geq 10$. By using a reliability index, the paper also pointed to the advantage of design approach DA 2. A set of pile capacity values is determined using the probability density function of normal distribution PDF and cumulative probability function of normal distribution CDF. When combining deterministic and probabilistic approaches in analysing the pile bearing capacity, the $R_{c,d}/P_u = 1.147$ ratio is found to be authoritative for design approach DA 2. Based on the developed CDF curves it is possible to establish relations for other levels of probability $P$ (higher or lower) as well, and it is also possible to consider higher and lower levels of reliability index. Values of partial resistance factors $\gamma_b,\gamma_s \approx 1.1$ are determined by analysing the reliability index, which also points to the authoritative design approach DA 2.

Table 3. Calculated values of reliability index $\beta$ across all design approaches (DA 1, DA 2 and DA 3) and coefficients of variation $C_r$ and the corresponding partial resistance factors $\gamma_b,\gamma_s$.

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<tr>
<th>$C_r$ (%)</th>
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<th>$\gamma_b$</th>
<th>$\gamma_s$</th>
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ACKNOWLEDGEMENTS

The work reported in this paper is a part of the investigation within the research project TR 36043 supported by the Ministry for Education, Science and Technological Development of the Republic of Serbia. This support is gratefully acknowledged (R. Folić).

REFERENCES

Probabilistic analysis of bearing capacity of piles with variable … Probabilistička analiza nosivosti stubova sa promenljivim …


ESIS ACTIVITIES
CALENDAR OF CONFERENCES, TC MEETINGS, and WORKSHOPS

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http://www.geologismiki.gr/products/cpet-it