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Evaluation of bearing capacity of cast in place piles from in situ tests based methods

Évaluation de la capacité portante des pieux coulés en place des méthodes in situ

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ABSTRACT Different in situ based methods are used for determining the bearing capacity of a single pile. For this reason, this paper aims to deal with evaluation of bearing capacity of a single cast in place pile, by using various methods based on three different in situ testing techniques: Standard Penetration Test (SPT), Cone Penetration Test (CPT) and Dilatometer Marchetti Test (DMT). These tests are used in this study to identify the soil profile and also to characterize the strength parameters of the soils, which are further used to estimate the bearing capacity. The tests are carried out in different locations in Albania, including also some coastal areas. The soil profile identified in all the sites is non homogeneous. From site investigations are determined various sandy and clayey layers, but in the coastal sites also organic material is present. The considered cast in place pile diameters, in this paper, range from 0.5 m through 2.0 m and embedment lengths range from 10 m, 20 m and 32 m. At the end of our study, the results of bearing capacities by different methods are compared. Some conclusions are highlight related to the use of in situ tests during the pile foundation design.

RÉSUMÉ Différentes méthodes basées sur le résultats des in situ test sont utilisés pour déterminer la capacité portante d'une seule pile. Pour cette raison, le présent document vise à répondre à l'évaluation de la capacité d'un seul coulé sur place tas portant, en utilisant diverses méthodes basées sur trois différents in situ des techniques de test: Standard Test de pénétration (SPT), Cone test de pénétration (CPT) et Dilatomètre Marchetti test (DMT). Ces tests sont utilisés dans cette étude pour déterminer le profil du sol et aussi pour caractériser les paramètres de résistance mécanique des sols, qui sont ensuite utilisés pour estimer la capacité portante. Les tests sont effectués à différents endroits en Albanie, y compris aussi des zones côtières. Le profil de sol identifiés dans tous les sites est non homogène. À partir du site enquêtes sont déterminés différentes couches sableux et argileux, mais dans les sites côtiers ont également la matière organique est présente. Le casting compte dans les diamètres lieu de pieux, dans ce document, la gamme de 0,5 m par 2.0 m et encastrement longueurs varient de 10 m, 20 m et 32 m. A la fin de l'étude, les résultats de roulement par des méthodes différentes capacitésont comparées. Certaines conclusions sont fort liés à l'utilisation de tests in situ lors de la conception de la fondation sur pieux.

1 INTRODUCTION

The criterion on the design of vertically loaded piles is governed by ultimate load bearing capacity and maximum settlement of the pile. The allowable axial load capacity of piles was initially based only on Standard Penetration Tests (SPT), but in recent years, determining bearing capacity of piles using the data taken by Cone Penetration Tests (CPT) is becoming a common practice in geotechnical design. Also Flat Dilatometer Marchetti Test (DMT) is used as a complement of static and dynamic loading tests and analysis for pile bearing capacity evaluations. But, still there are lots of uncertainties in the accuracy of the data taken by in situ tests, related to the testing techniques, soil conditions, etc.

Several methods have been developed to overcome the uncertainties, which include simplifying assumptions and empirical approaches.

Bearing capacity of cast in place piles in this paper is determined by using 5 methods based on SPT data, 4 methods based on CPTU data and 1 method based on DMT data.

In order to consider the maximum settlement of a pile, the load - displacement curve of one static axial loading test is compared with the load - displacement curve obtained by finite elements method analysis of a single vertically loaded pile, where the soil parameters used in the model are obtained by in situ tests.

2 PROJECT DESCRIPTION AND SITE INVESTIGATION RESULTS

The data from three different projects in Albania are engaged to conclude with pile bearing capacity predictions of the vertically loaded cast in place piles.

The first project is located in the sandy beach of Semani, near Fier city. Five boreholes, including also the SPT tests carried out in them and 5 CPTU tests are considered for this project. The pile embedment depth is accepted equal to 20.0 m and the diameters of the piles vary from 0.50 to 2.00 m. The second project is located in the sandy beach of Porto Romano, 10 km far from Durresi city. The site investigation program included 3 CPTU tests and 1 DMT test. From the results of CPTU tests, carried out in this project are estimated the N values of SPT, form where are derived than other geotechnical parameters to be involved in the approaches for bearing capacity calculations by SPT tests based methods. The embedment depth of the piles in this project is accepted 10.0 m and the diameters of piles vary from 0.50 m to 2.00 m. The third project considered in this paper is Durresi Bypass. The site investigation program for this project included traditional drillings. In each borehole are carried out some SPT tests. From SPT results are also derived the CPT parameters, which are involved in the calculations of pile bearing capacity by CPT based methods. Part of the site investigation program of this project was also a static axial loading test, which was carried out on a cast in place pile with the embedment depth equal to 32.0 m and the diameter equal to 1.20 m. The load – displacement curve exhibits a well defined failure condition. Based on the loading test results, this pile is designed to work under working load equal to 3330 kN. A schematic layout of the static axial loading test is presented in Figure 1.

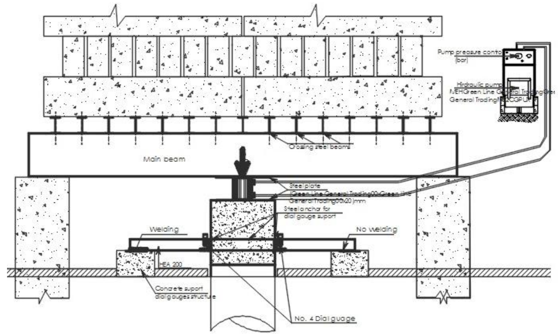

Figure 1. Schematic layout of static axial loading test.

In Table 1 are presented the applied loads for each loading phase, until the end of the tests at 150% of working load. (Anamali 2014)

Table 1. Applied load for each loading phase and the corresponding settlement of pile.

Working Load (%)	Load (kN)	Settlement (mm)
25	833.3	0.305
50	1666.5	0.570
75	2499.8	0.995
100	3333.0	1.798
125	4166.3	2.677
150	4999.5	3.933
200	6666.0	6.520
250	8332.5	10.705
300	9999.0	17.620

IN SITU TESTS BASED METHODS FOR PILE BEARING CAPACITY EVALUATION

2.1 SPT based methods

In this paper, five direct methods, which involve in calculations the N values of SPTs, are used to evaluate the bearing capacity of piles. The N values of SPT are corrected for each method. The methods used in this paper are: Decourt, 1995 (Shooshpasha et al. 2013), Aoki & De'Alencar (Shariatmadari et al. 2008), Shioi & Fukui (Shariatmadari et al. 2008), Japanese Practice (Shkodrani 2011) and O'Neill & Reese (Coduto 2001).

2.2 CPT based methods

Four of the most highly accept methods for their depicted well efficiency in pile design are used in allowable axial load capacity evaluation based on direct measurements by CPT. These methods are: Eslami & Fellenius (Fellenius 2009; Shnaid 2009), Bustamante & Gianiselli (LCPC) (Lunne, Robertson, Powell 1997; Robertson 2012; Shnaid 2009), de Ruitter & Beringen (Lunne, Robertson, Powell 1997; Robertson 2012; Shnaid 2009), Zhou et al. (Hu 2007). The uncorrected cone resistance, q_c was used in Bustamante & Gianiselli, de Ruitter & Beringen and Zhou et al. The Eslami & Fellenius method engage in calculations the measured pore pressure, since q_t is used instead of q_c.

2.3 DMT based method

Only one method based on DMT data, developed by Powell et al. (Powell et al. 2001), is considered in this paper.

3 RESULTS AND DISSCUSIONS

In this session, the results of the allowable axial load capacity evaluated by the in situ based methods mentioned above are presented graphically in Figures 2, 3, 4, 5 and 6. The considered factor of safety for all the calculations is FS = 3.0. The graphs shown below present the variation of the allowable axial load capacity of piles for different diameters of piles.

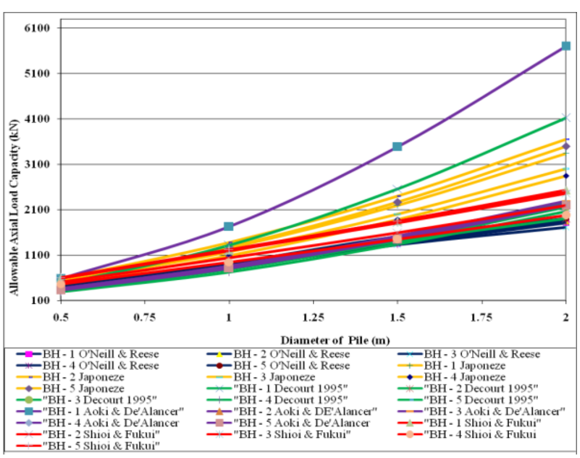

Figure 2. Project 1 – Results by SPT (D = 20 m).

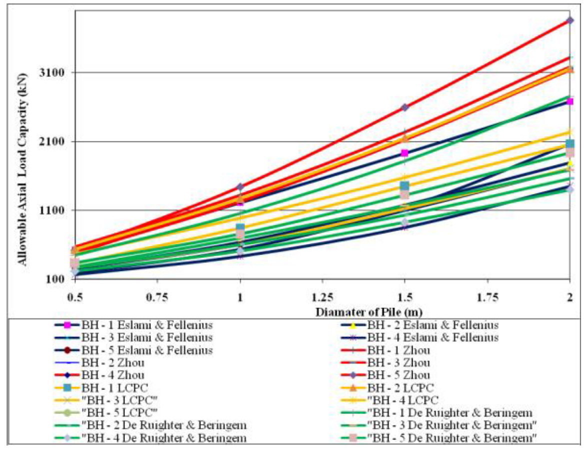

Figure 3. Project 1 –Results by CPTU (D = 20 m).

The pile embedment depth in the calculations for this project are 20.0 m. The diameters of the piles vary from 0.50 until 2.00 m. The difference of allowable pile capacity for different methods is noticed in Figures 2 and 3. The results of allowable pile capacity according the SPT based methods vary from 292 kN to 5696 kN. The results obtained by CPT based methods predict the allowable pile capacity from 168 kN to 3862 kN.

The piles embedment depth for Project 2 are 10.0 m. The diameters of the piles vary from 0.50 until 2.00 m. The results of the allowable axial load capacity evaluated by SPT, CPTU and DMT based methods are shown in Figures 4 and 5. The N value of SPT in this project is derived by the CPTU tests results. The allowable capacity of piles, from SPT data vary from 197 kN to 17614 kN. The allowable axial load capacities evaluated by CPTU based methods vary from 437 kN to 16521 kPa. According the DMT based method, the allowable capacity vary from 538 kN to 3619 kN.

In Project 3, the piles embedment depths are equal to 32.0 m and the diameters of piles also vary from 0.50 m to 2.00 m. The results of calculations for this project are shown in Figure 6. The results obtained by SPT based methods vary from 542 kN to 6095 kN. Meanwhile, the values of the allowable axial load capacity obtained by CPT based method, which involve the CPT data derived by N values of SPTs, vary from 635 kN to 6153 kN.

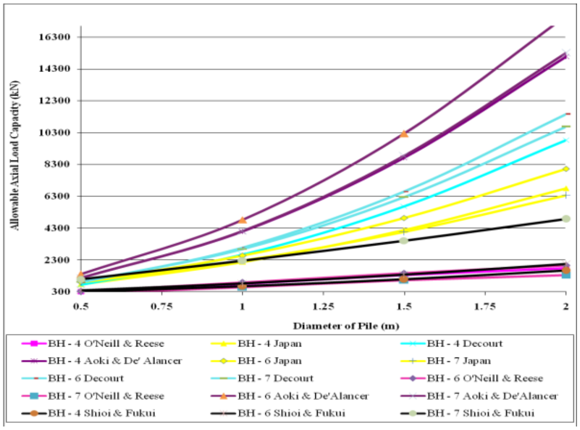

Figure 4. Project 2 – Results by SPT based methods (D = 10 m).

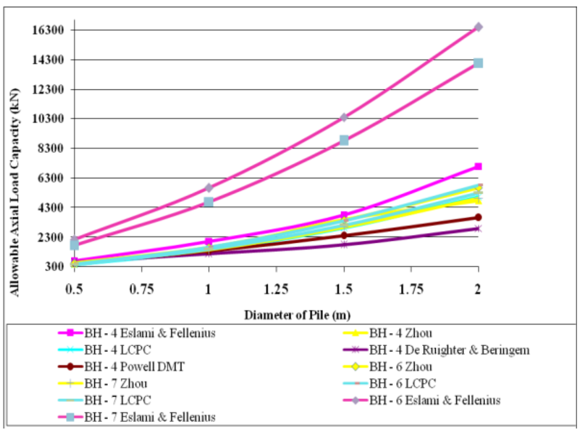

Figure 5. Project 2 – Results by CPTU & DMT (D = 10 m).

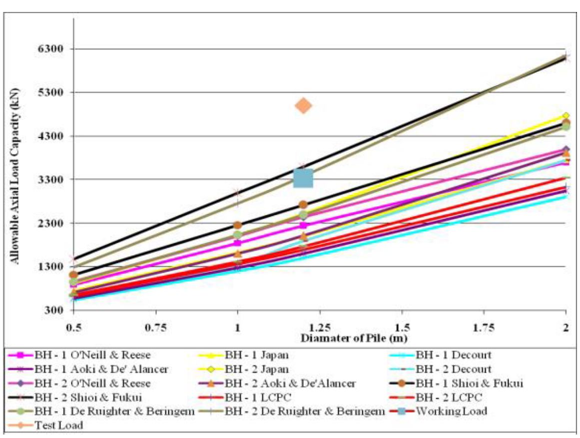

Figure 6. Project 3 – Results by SPT & CPT (D = 32 m).

For the SPT based methods, the predicted capacities by Shioi & Fukui method are higher than the results predicted by other methods.

For the CPTU based methods, the predicted capacities by Eslami & Fellenius method are higher than the results predicted by other methods.

Although the differences of allowable axial bearing capacity of piles are notable in each project considered in this paper, the validation of the results is done only for Project 3, where the static loading test is carried out. In order to conclude the validation of the results obtained by different methods, statistical approach and numerical analysis by finite element method are used. The first validation, by statistical approach presented below, is used to verify the SPT and CPT based methods. The second validation of the results consists on the comparison between the load - displacement curves obtained by static loading test in site and the PLAXIS 2D FEM simulation.

4 VALIDATION

4.1 Statistical Approach

A statistical approach is engaged to verify the SPT and CPT based predictive methods. The value of Q_p/Q_m is a measurement of the tendency to overestimate or underestimate the pile capacity. The closer to a ratio of unity, the better is the agreement (Sharimadari et al. 2008).

To estimate the average error, Equation (1) can be used:

$$E = \left(\frac{P_{up}}{P_{um}}\right) - 1 \tag{1}$$

Where:

P_{up} – Predicted capacity of pile;
P_{um} – Measured capacity of pile

Also, the mean and the standard deviations are calculated by using Equations (2) and (3), given below:

$$\mu(E) = \frac{1}{n}\sum_{i=1}^{n}(E) \tag{2}$$

$$\sigma(E) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left((E)-\mu\right)^2} \tag{3}$$

In Table 2 are presented the results of statistical validation for the allowable capacity of piles.

Table 2. Statistical validation for allowable capacity of piles.

Design Method	Arithmetic Mean (μ)	Standard Deviation (σ)
Decourt (1995)	0.0224	0.167
Aoki & De' Alencer	0.0854	0.176
Shioi & Fukui	0.8975	0.374
O' Neill & Reese	0.0374	0.033
Japanese Practice	0.4067	0.087
LCPC	0.3611	0.216
De Ruitter & Beringen	0.7622	0.377

From the results of the statistical validation is notable that according O' Neill & Reese method, based on SPT data, the standard deviation has a lower value. The requirement of this project was to load the pile until 150 % of the working load. Considering this requirement, for this project, O'Neill & Reese and Japanese Practice show a lower values of the deviation than the other methods.

4.2 Load – Movement Curves from static loading test and numerical simulation by FEM

An attempt to study the load - displacement curve by numerical simulation using finite element method, to analyze a pile, which is 1.20 m in diameter and 32.0 m in embedment depth is made in this paper.
The finite element method in PLAXIS 2D V.8 is used for this purpose (Brinkgreve 2002). The load - displacement curve generated by this numerical simulation is compared with the load - dispacement curve obtained by the field results. As in the field, the PLAXIS 2D analysis consists in six layers of soil. First 3 layers are sandy silts to silty sands, the fourth layer is silty clay, the fifth layer is fine sand and the last one is silty clay to clayey silt.

The pile considered in this analysis, has been modeled as an axisymmetric pile. The 15 nodes triangular elements has been choosen for both pile and soil layers. The standard fixities PLAXIS 2D tool to define the boundary conditions are used. These boundary conditions are generated according 2 simple rules: vertical geometry lines obtain a horizontal fixity (u_x = 0) and horizontal geometry lines in the model obtain a full fixity ($u_x = u_y$ =0). The soil structure interaction is modeled using and elastic - plastic behavior of the interfaces. The interface element properties are considered the same as soil properties. The strength reduction factor for the interface R_{inter} = 0.90 is used.

In this numerical simulation the water level is put at 1.0 m, according the measurements in field (Anamali , 2014). Strength parameters of soils are derived by SPT tests. The layers of soils are modeled in underained conditions in PLAXIS 2D. The Hardening Soil Model (HSM) is used for each soil layer, to consider the differences in stiffness during the loading and unloading/ reloading parts. The strain hardening is assumed to be isotropic, depending on the plastic shear and volumetric strains. A total of 10 input parameters are required in this model (Shanz et al., 1999). The pile model used is linear - elastic, non porous. Its unit weight is considered 25 kN/m^3 and the Modulus 3.0x10^7 kPa. Figure 7 shows the generated mesh. Boundary dimensions 5.0 m X 40.0 m are optimal, because a decrease in dimensions results with poor results, whereas an increase in the boundary dimensions will not influence them (Wehnet M. and Vermeer .P.A., 2004).

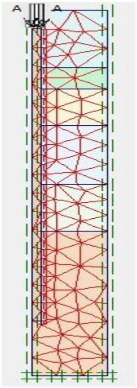

Figure 7. Generated mesh in the axisymmetric pile model

The Load – Displacement Curve in this numerical simulation is obtained by applying the load into 12 different phases, same as during the static loading in site. The commonly used criteria for interpreting pile capacity is the Davvison Criteria, which is presented in Equation 4 (Coduto, 2001).

$$PL/AE + D/120 + 4 \text{ (mm)} \tag{4}$$

The settlements in Project 3 for 150% of working load by static loading test are calculated by using the Equation 5, given below:

$$2\%\ D+0{,}5\ PL / EA \tag{5}$$

The Load – Displacement Curve obtained by PLAXIS 2D FEM analysis is presented in Figure 8. As shown from the graph in Figure 8, for 150% of working load, which corresponds to the axial load equal to 5000 kN, the settlement in the field are estimated equal to 3.933 mm. For the same load the settlement estimated by the numerical simulation with finite element method in PLAXIS 2D is equal to 8.670 mm. Considering the maximum value of settlement and the load - displacement curves, the pile has a greater allowable axial load capacity than 150% of working load.

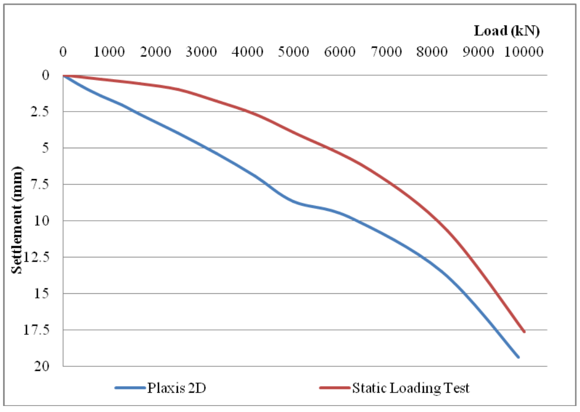

Figure 8. The load – movement curve from PLAXIS 2D from SPT data.

From Figure 8, is shown that the curves obtained by field test results and PLAXIS 2D analysis are close to each other, which implies that the numerical simulations can be applied.

5 CONCLUSIONS

Considering that SPT is the most common test in geotechnical practice, because of its simplicity and cost effectiveness, SPT based methods are widely used for allowable axial load capacity of piles. But still a lot of deficiencies exist in these applications. To overcome these problems, CPT based methods are developed. Among all the methods available, Bustamante and Gianiselli method is the most accurate in clay soils, whereas de Ruitter and Beringen and Eslami and Fellenius are very efficient approaches to predict the pile capacity in sandy soils. Although the big similarity between a pile and a cone, there are many factors that affect the results of allowable axial load capacity, which can be attributed to the good agreement between the method used and soil behavior, differences between the pile and cone diameters, the different pile - soil and cone - soil interfaces, correlation factors used, etc. Considering all the methods used in this paper, it is notable that the best method for evaluation of allowable bearing capacity of a pile is the static load test.

By numerical simulation using the finite element method the back – analyze of the static loading test, in an axisymmetric pile model was made. The analyze showed a very good agreement between the load - displacement curve by field measurements and the load - displacement curve generated by the numerical simulation.

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