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Deep foundations of the new Pavilion 37 – fair quarter Bologna

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ABSTRACT: The present paper concerns the design of driven precast tapered piles, that have been used within the project of the new Pavillion 37 of the fair quarter of Bologna. A particular focus will be reserved to the evaluation of the axial bearing capacity of these elements and to the prevision of their load-settlement curve. The geotechnical characterization, as well as the prediction of the axial resistance of the piles, has been mainly based on Cone Penetration Test with piezocone CPTu. The previsions will be compared with the results of a series of static load tests performed during the construction.

1 INTRODUCTION

The present paper concerns the design of deep foundation for a new exhibition hall, especially as regard the prediction of the axial bearing capacity of the piles and of their load-settlement curve.

The framework of the project and the geometry will be described first, following with the description of the geotechnical campaign and the soil characterization. Then we will assess the project prediction by comparison with the results of the static load tests performed on-site during construction.

All these evaluations are based on CPTu test, as described in the following.

2 PROJECT DESCRIPTION

Within the revamping project of the fair quarter of Bologna, the new Pavilion 37 rises as flagship of the exhibition centre with its remarkable opening roof and its planimetric dimensions of 80 x 184 meters (Figure 1). The steel structure of the roof stands on 8 reinforced concrete towers, whose foundations represent the most important and complex geotechnical elements of the whole project.

The choice was to adopt deep foundation for all the RC towers, consisting in driven precast tapered piles arranged in groups (Figure 2). The adoption of deep foundation was basically justified by the high loads transmitted by the roof, together with the geotechnical conditions of the site.

The whole project concern also two other adjacent buildings (the so-called “Mall” and “East entrance”), not object of the present paper, whose foundations have been designed similarly.

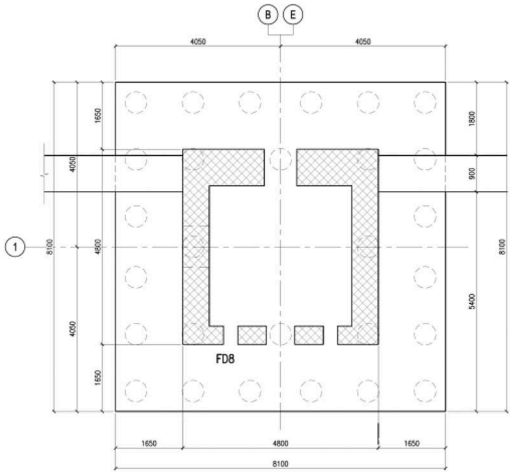

Figure 1. Typical deep foundation of the RC towers supporting the roof of the pavilion.

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3 PILE DESCRIPTION

Driven precast tapered piles were used in the project. The choice was due to different aspects, both geotechnical and construction-related:

- Driven piles have good geotechnical performances. In addition, because of the installation process, an increase in density is induced in the soil.
- They are rapid to install and it is possible to control the performance of piles during driving.
- In soft soils or in presence of water neither predrilling nor hole support are required.
- There is no excavation material, so the organization of the construction site is clean and easier.

The adopted piles have a diameter of 53/26 cm (head/toe), a taper of 1.5 cm/m and a length of 18 meters. The piles were precasted in factory with a specific centrifugation process.

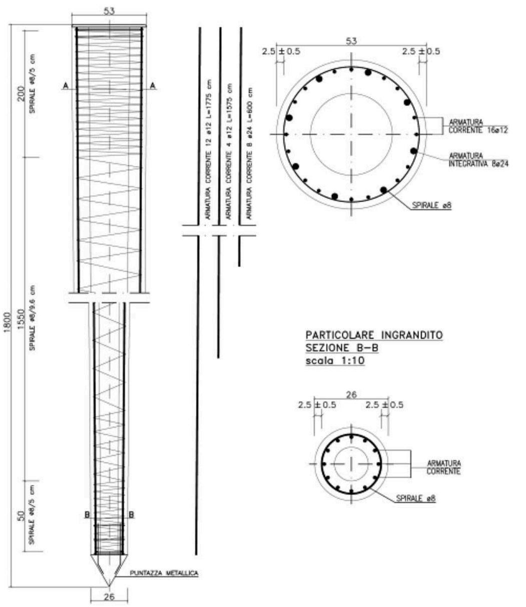

Figure 2. Typical tapered precast pile with length L= 18m. Vertical sections and reinforcements.

For driving were used hydraulic hammers with weight of 6 and 7 tons. The driving energy was 36 kNm and the settlement during driving was measured in the range from 5 to 7 mm/blow.

4 GEOTECHNICAL CHARACTERIZATION

The site was characterized by performing an investigation campaign consisting mainly in on-site soundings. Four cone penetration tests with piezocone CPTu, a borehole (with soil sampling and SPTs) and geophysical MASW and HVSR tests have been carried out.

The geotechnical characterization is mainly based on the interpretation of the performed CPTu. They are very effective in recognizing soil behavior and strength and stiffness parameters. In Figures 3, 4 and 5 some of the principal results from the interpretations are showed.

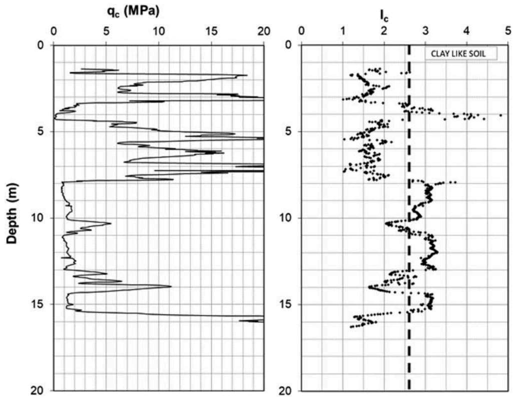

Figure 3. Point resistance and soil index vertical profiles from the interpretation of one of the performed CPTu.

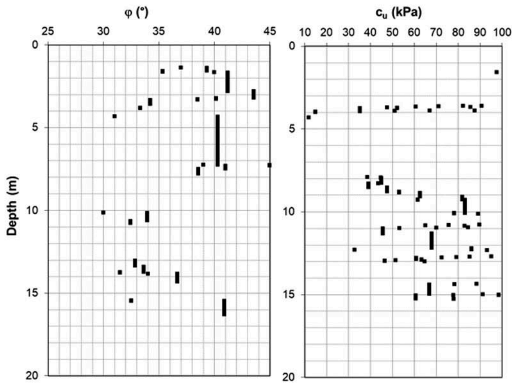

Figure 4. Friction angle and undrained strength vertical profiles from the interpretation of one of the performed CPTu.

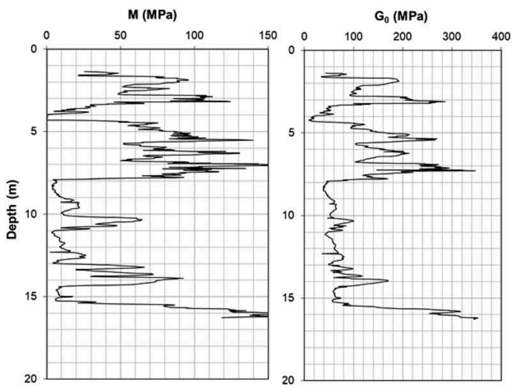

Figure 5. Confined and initial shear moduli vertical profiles from the interpretation of one of the performed CPTu.

An alternation of coarse-grained and fine-grained material was found out, described by the following geotechnical model (Table 1).

Table 1. Geotechnical model.

Layer	From - To [m]		Undr. strenght c_u [kPa]	Effective cohesion c' [kPa]	Friction angle φ [°]	Tangent modulus E_0 [MPa]
Sandy silt	0.0	8.0	-	0	32-34	200-250
Clay	8.0	15.0	60-70	5	27-30	120-170
Sandy gravel	15.0	20.0	-	0	38-40	≥ 500
Sandy to clayey silt	20.0	35.0	70-80	5	27-30	300-350

Soil stiffness was described in terms of the initial tangent modulus because the deep foundations have been analysed adopting a numerical BEM (Boundary Element Method) approach with the software Repute, developed by Geocentrix (Bond & Basile 2010, Basile 1999).

5 BEARING CAPACITY OF PILES

In the design phase, pile axial capacity has been predicted adopting calculation methods directly correlated to CPTu.

Then, during construction, pile capacity has also been evaluated by interpreting the measured load-settlement curves derived from the pile load tests, in order to validate the design predictions.

5.1 *Analytical evaluation of pile capacity*

We referred to different methods based, directly or indirectly, on CPTu tests. The first is the method proposed by Eslami & Fellenius (1997). In this case the beneficial effect of tapering has been taken into account by increasing the shaft capacity by a factor that, as from Nordlund (1963) and Horvath (2002), varies between about 1.5 for clayey-like soil layer to 2.0 for sandy ones. An example is reported in Figure 6.

The second method is the one proposed by Togliani (2010). This method, in particular, is specific for tapered piles and is able to directly evaluate both the shaft capacity of the pile, related to its side area, and the component related to the tapering benefit.

The axial ultimate capacity of the tapered piles, predicted applying the previous methods, is reported in Table 2, the values are referred to a limit settlement of about 10 mm.

5.2 *Load tests interpretation*

Four static load tests have been performed on the L= 18 m tapered piles during construction, as part of the acceptance testing, under a maximum vertical load approximately equal to 1.5 time the exercise load (Figure 7). The results obtained from acceptance testing are well aligned to the design prediction from direct correlations with CPTu, considering also that these load tests have not kept to failure but were intended to verify the correct installation and performance of the piles.

Moreover during the construction of a nearby building two static load tests were performed, on the same type of pile, reaching loads of 2000 kN and 2400 kN. These last two load tests have been interpreted according to the approach proposed by Chin (1970) to evaluate the ultimate capacity of the tested pile, in Figure 8 an example of the interpretation is proposed.

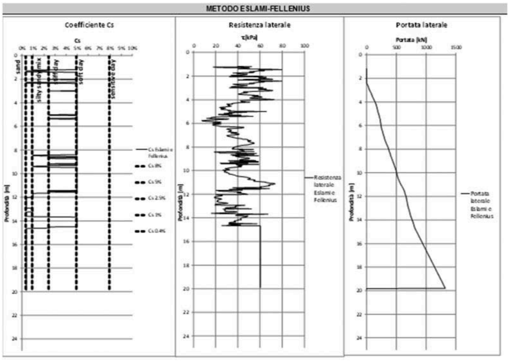

Figure 6. Tapered pile axial capacity evaluation from CPTu adopting the Eslami & Fellenius method.

Table 2. Pile axial ultimate capacity from CPTu.

	Shaft capacity [kN]				Base capacity [kN]	
	Eslami&Fellenius		Togliani			
CPTu sounding	Shaft	Taper benefit	Shaft	Taper benefit	E & F	Togliani
CPTu 1	1322	794	1306	843	340	385
CPTu 2	1593	956	1536	1180	367	416
CPTu 3	1502	1201	1527	1354	394	441
CPTu 4	1364	1228	1556	1480	344	378

6 LOAD-SETTLEMENT CURVES PREVISION

The load-settlement curves, representing the response of the single pile, have been predicted adopting an analytical model (Randolph & Wroth 1978), two numerical approaches by BEM analysis with the software Repute and by FEM analysis with the software Plaxis and adopting a mixed approach based on the cavity expansion theory (Dei Svaldi et al., 2012).

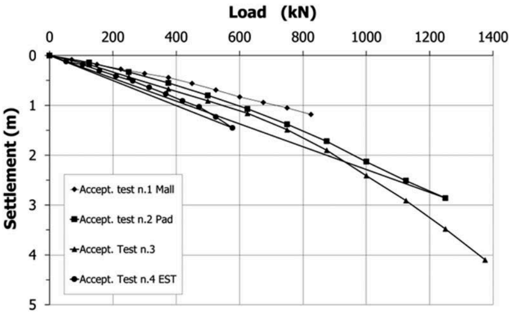

Figure 7. Acceptance testing curves.

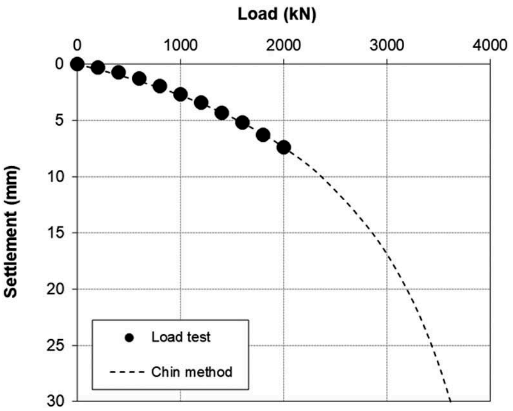

Figure 8. Interpretation of the static load test n.1 with the Chin method.

All these predictions were based on the parameters of the geotechnical model obtained from CPTu tests (Table 1).

After carrying out the load tests, the measured curves have been compared to the predicted ones, finding out what is graphically represented in Figure 9.

The design prediction does not deviate much from to the experimental measures, and generally show a lower stiffness with respect to them, giving to the foundation design a certain margin of safety.

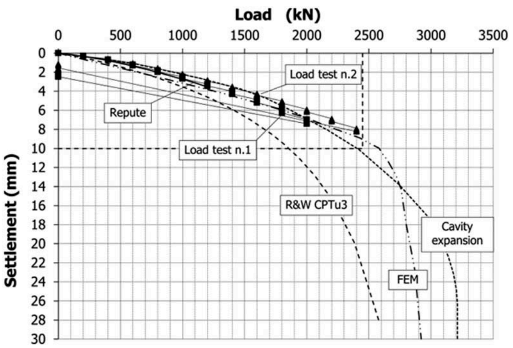

Figure 9. Load-settlement curves: comparison between design predictions and load tests.

On the basis of the load-settlement curve for the single pile, a calibration analysis of the model of the deep foundation of the RC tower was carried out, by evaluating with different methods the settlements under the action of the vertical load (15785 kN). The foundation consists of a reinforced concrete raft 1.6 m thick resting on 28 tapered piles (Figure 2).

For the calibration has been adopted the following methods: the formulation proposed by Mandolini (1994), the BEM method and the traditional multi-layer one-dimensional method, where the pile-soil system was considered as a layer with stiffness modulus (Table 3) evaluated through an interaction analysis between pile, plate and soil based on the concept of efficiency (Fleming et al., 1992). Table 4 reports the results of the calibration analysis.

Table 3. Equivalent stiffness modulus of soil-pile system.

η_w	0.280	efficiency	
K_p	525	MN/m	single pile stiffness
K_{pg}	148	MN/m	pile group stiffness
E_{eq}	1108	MPa	

Table 4. Settlement of RC tower under vertical load.

	Settlement (mm)
Mandolini	
BEM	3.94
Equivalent stiffness	3.8

Once calibrated the BEM method was used to study the behaviour of the RC tower under the different load combinations in compliance with the Italian Technical Standards for Buildings (DM 17.01.2028).

An example of settlements and pile reactions under the action of ultimate state loads, obtained from BEM analysis, are shown in Figure 10.

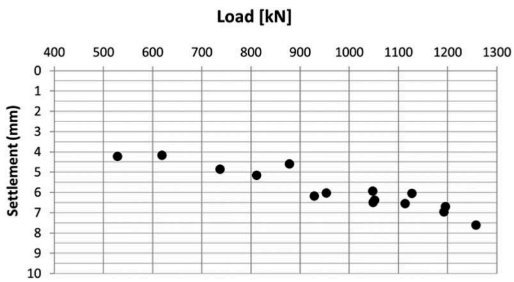

Figure 10. RC tower - settlements and reactions of the piles obtained from BEM analysis under USL loads.

7 CONCLUSIONS

The interpretative criteria of the CPTu tests allow to reliably define the stratigraphy and the mechanical characteristics of the soils at the basis of the foundation design.

For a complete design of the piled rafts it is not only important to calculate the bearing capacity of piles but also to define their behaviour through the construction of the load-settlement curve. In this context, it is possible to use complex numerical models but also simpler methods which, in any case, allow to obtain usable results for the design.

A final aspect to highlight is that in order to obtain reliable results in complex analyses with numerical methods, the calibration by comparing the results of simple analyses with other calculation methods is relevant.

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