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The estimation of vertical and horizontal pile bearing capacity

L'estimation de la capacité portante verticale et horizontale des pieux

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ABSTRACT: A cooling tower of a thermal power plant recently built in Slovenia required a foundation system made of 30.00 m long piles. Because of a large number of piles, the reduction of their length could lead to significant savings. To investigate such possibility, it was necessary to study all factors that contributed to the bearing capacity of piles, especially the amount of load transferred to the soil through the pile skin. Therefore, the vertical and horizontal static load test of one pile was performed on the construction site. The test pile was equipped with improved strain sensors built into the pile body. During such load tests in most cases only vertical bearing capacity is investigated, but in this case also horizontal load test was performed since a massive concrete reaction frame was built to assure the support for the hydraulic jacks used for the introduction of the vertical and horizontal load as well. During the vertical test the vertical load was increased until the soil below the pile toe collapsed. When the pile was loaded in horizontal direction the load was increased until the pile failure occured. Because of a large number of measuring points distributed along the pile longitudinal axis it was possible to estimate the position of breakage point and the distribution of stresses in the pile and on the contact surface between the pile and soil through all loading stages.

RÉSUMÉ: La tour de refroidissement d'une centrale thermique récemment construite en Slovénie nécessitait un système de fondation sur pieux de 30,00 m de longueur. En raison d'un grand nombre de pieux, la réduction de leur longueur pourrait entraîner des économies importantes. Pour étudier une telle possibilité, il était nécessaire d'étudier tous les facteurs qui ont contribué à la capacité portante des pieux, en particulier la quantité de charge transférée au sol à travers le revêtement de pieux. Par conséquent, les essais de chargement statique vertical et horizontal d'un pieu ont été effectués sur le chantier de construction. Le pieu d'essai était équipé de capteurs de déformations améliorés intégrés dans le fût du pieu. Lors des essais de chargement, dans la plupart des cas, uniquement la capacité portante verticale est étudiée, mais dans notre cas un essais de chargement horizontal a été également effectué, car un cadre de réaction en béton massif a été construit pour assurer le support des vérins hydrauliques utilisés pour l'introduction de la charge verticale et horizontale. Au cours de l'essai vertical, la charge verticale a été augmentée jusqu'à ce que le sol sous la pointe du pieu se soit effondré. Lorsque le pieu était chargé dans le sens horizontal, la charge était augmentée jusqu'à la rupture du pieu. En raison de nombreux points de mesure répartis le long de l'axe longitudinal du pieu, il a été possible d'estimer la position du point de rupture et la répartition des contraintes dans le pieu et sur la surface de contact entre le pieu et le sol à travers toutes les étapes de chargement.

Keywords: measurement technology, pile foundation, pile load test, elasto – plastic model, stress - strain analysis

1 INTRODUCTION

The implementation of deep foundations is relatively expensive, therefore in cases where a large number of piles is foreseen to assure the sufficient bearing capacity of structure foundations it is wise to consider whether it is possible to rationalize the foundation construction. Direct savings of costs can be achieved in the case of length and/or diameter reduction of pile foundations (Škrabl, 2002). When the length of certain pile is reduced, its base is no longer in solid material, and therefore the bearing capacity of pile shaft becomes more important. Although the pile design analysis generally involves the calculation of bearing capacity (composed of shaft and base bearing capacity) and the estimation of the possible deformations under working loads, the important characteristics of particular soil-pile interaction can be reliably assessed only if the actual field loading test is carried out. The load test should simulate the real load history as accurately as possible, but on the other hand it has to be performed as quickly as possible to be efficient and useful. Several testing methods have been designed to respond to both opposite requirements (ASTM, 2007; Reese and Van Impe, 2011). Two mostly used of them are dynamic and static load test.

Static tests are the most commonly used in the general practice. This testing method is characterized by a set of stages where a constant load is applied on the pile head during a given duration. The load is monotonically increased until reaching the maximum load. After that the applied load is progressively unloaded to zero. The load is applied by hydraulic jacks, weighted platform or adjacent tension piles or soil anchors are used to provide the reaction for the load applied on the pile. The dial gauges are fixed on a reference frame to perform displacement measurements of pile head. The applied load is simultaneously measured using load cells or calculated from the known pressure values of the jack system. Since a loading test should provide useful information about pile shaft bearing capacity, the improvement of the measurement technology is needed. This improvement includes additional strain sensors distributed along the pile longitudinal axis.

Because of a large number of measuring points distributed along the pile longitudinal axis it was possible to estimate the position of failure point and the distribution of stresses in the pile and on the contact surface between the pile and soil through horizontal loading stages.

2 TESTING SITE AND LOADING PROCEDURE

2.1 Testing site

The test pile was conducted outside the extent of future cooling tower (Štrukelj and Macuh, 2010).

As the vertical load was provided by hydraulic jacks (Figure 2) and not by kentledge (a mass of heavy material placed on a platform constructed on the head of a pile), it was necessary to assure sufficient spatial rigid reaction frame, which served as a support for hydraulic jacks used for the implementation of planned phases of loading. The reaction frame was made of two concrete mutually perpendicular 3.00 m high and 0.50 m wide beams crossing each other at the middle of their spans. (Figure 1).

Figure 1. Testing site with reaction frame

The intersection of the beams was situated directly above the head of a test pile. Both beams were connected on each of their ends to a 30.00 m long tension pile in order to assure enough anchoring capacity during the loading process.

Figure 2. Hydraulic jacks for applying the vertical load

2.2 Loading procedure

According to expected ultimate horizontal load (2400 kN) only one hydraulic jack was used for loading in horizontal direction (the lower right corner of Figure 2). The horizontal force was applied to the pile head from eastern direction and for the support of the hydraulic jack during the loading process the eastern one of four piles supporting the reaction frame was used. This pile was additionally reinforced to sustain the horizontal loading. The aforementioned value of horizontal load was actually achieved in the last loading stage, but during loading the fracture of the pile occurred.

During the horizontal test the load was applied in steps. The test began with the preload (350 kN) and after 15 minutes when the displacements calmed down the pile was unloaded. The loading then went on in equal steps of 350 kN in regular time intervals of 30 minutes until the final load value was reached. The unloading process was incremental taking the same loading steps, only the time intervals between them were shorter (15 min). The maximum horizontal displacement of the pile head (239.8 mm) at the last loading stage (2250 kN - 150 kN less than expected) corresponded to the maximum extension of hydraulic jack in extended position.

3 PILE INSTRUMENTATION

Since geodetic measurements were not continuous, the exact time of measuring was recorded together with measurement results in order to synchronize and compare the geodetic and electronic displacement measurement results (Figure 3).

During the horizontal load test the horizontal displacements were measured using the same inductive displacement transducers as before. They were attached to the scaffold construction in horizontal position. With the first two transducers the pile head displacements were measured and with the other two the lateral displacements of the pile supporting the hydraulic jack were measured (Figure 4).

Figure 3. Geodetic measurement points on pile head (horizontal displacements) and on the eastern pile of the reaction frame (lateral displacements)

Since the maximum extension of used deal gauges is 100 mm and the expected horizontal displacements were greater than 200 mm, both transducers measuring horizontal displacements of the pile head had to be more times alternately moved to the new reference positions during the test to cover the entire displacement. To maintain the accuracy of electronic displacement measurements only one of two deal gauges which measured horizontal displacements of the pile head was moved at the time and from both measured signals these movements were later excluded. The electronic displacement measurements were verified also with geodetic equipment. For geodetic measurements of horizontal displacements two total stations were used.

Figure 4. Inductive displacement transducers during measurements of horizontal displace-ments of the pile head and lateral displace-ments of supporting pile

The test pile was also instrumented with sixteen special strain sensors[1] distributed in two vertical rows of eight sensors. They were built in the pile body in eight levels on two opposite sides of the pile to measure the normal strains in axial direction. Before pile concreting sensors were attached to the main reinforcement bars so that the first pair of sensors was 0.75 m above the pile toe, the next three pairs of sensors were positioned equidistantly 2.50 m from each other, followed by two pairs of sensors at a distance of 2.00 m. The last two pairs of sensors were installed at distances of two times 2.50 m. With eight levels of strain sensors the entire length of a pile from a pile toe to pile head was covered. The disposition of sensors is shown in Figure 5.

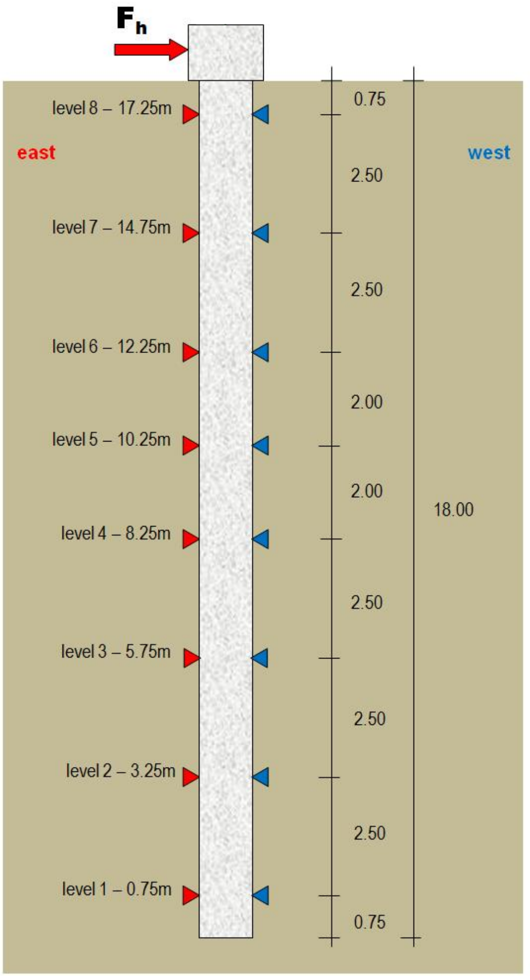

Figure 5. The disposition of strain sensors and directions of loading

4 ANALYSIS OF THE MEASUREMENT RESULTS

All measured results concerning the horizontal load test and corresponding calculations are

[1] Patent No. 22765, Department of Commerce, Slovenian Office of Intellectual Property

shown in numerical and graphical form in following chapters. In Figure 6 the time histories of horizontal displacements of a pile head and a reaction frame are shown as well as the diagram of horizontal load applied to pile head.

All displacements during the test were measured electronically using deal gauges and geodetically using total stations. All displacement measurements were synchronized in the same way as in the case of vertical load test. As can be seen in Figure 8 the matching of geodetically and electronically measured results was very good. Since the force intensity and corresponding horizontal displacements of the pile head are simultaneously measured the diagram of displacements versus applied load could be made (Figure 7).

For strain measurements the same strain sensors as at the vertical load test were used. For every one of eight measurement levels two strain values were obtained. Each of these values was calculated as an average value of two strains measured by two strain gauges built in each sensor. A diagram where averaged strain values versus the distance from the pile toe towards the surface for each sensor are shown for every loading step (Figure 8) is very indicative. The strain curves were plotted for strains measured on both opposite sides of the test pile. In Figure 8 can be clearly seen that the discontinuity in the pile occurred in the tensile zone of the test pile before applying the last loading step. The behaviour of the strain sensor at this point indicates that the 150 cm long reinforcement bar, which was the base of the strain sensor, lost contact with the concrete because of the large relative displacements in the crack zone.

It can be seen from diagram in Figure 8 that when the load intensity reached 1750 kN the strains below and above the level 14.75 m (the level where the pile collapse was assumed) began to reduce, since the material near crack relaxed. This phenomenon became more evident in the following two loading steps, when the shift of the pile neutral axis caused a significant increase of compressive strains on the opposite (western) side of the pile, which is characteristic for plastic hinges formation.

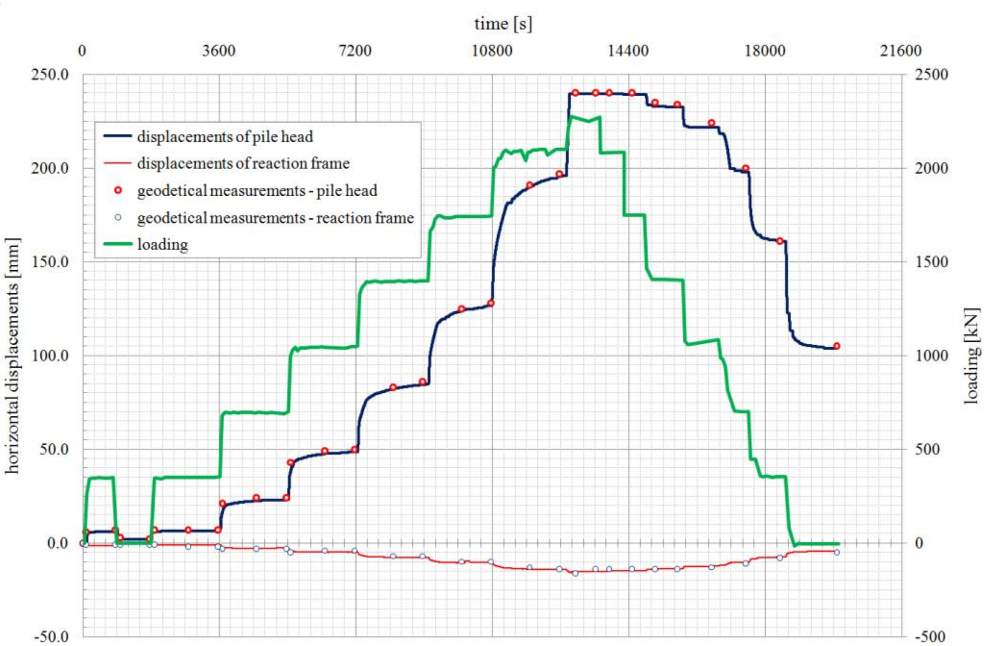

Figure 6. Time history of horizontal loading and displacements

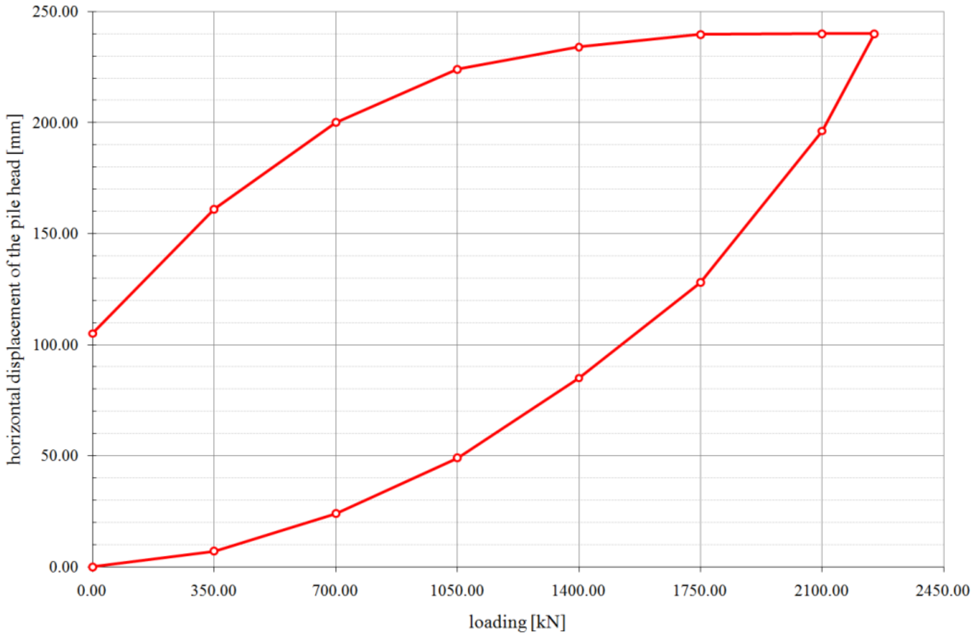

Figure 7. Horizontal displacements of pile head versus load intensity

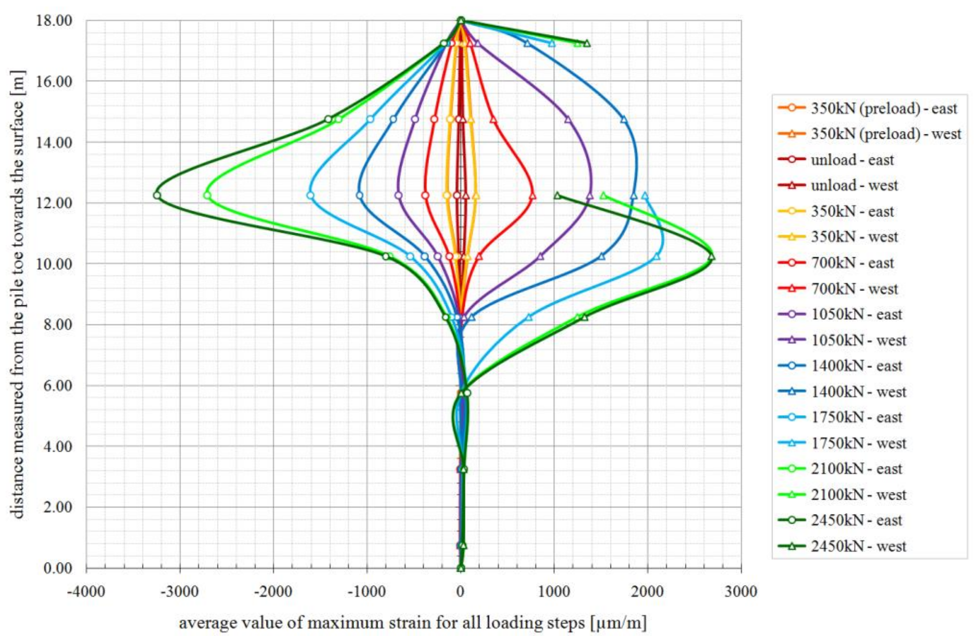

Figure 8. Average values of maximum strains versus distance from pile toe

A moment when the pile began to collapse can be clearly identified also in the Figure 8. Time history of horizontal loading and displacements, where the horizontal displacements at the loading step 1750 kN started to rise much faster than at the previous loading steps. Obviously in the last loading stage the pile completely collapsed since the horizontal displacement almost completely and without additional resistance followed the extension of the hydraulic jack. The above assessments are further confirmed by the behavior of the pile during the process of gradual unloading. At the first three unloading steps the horizontal displacement of the pile head remained almost on the level of the maximum value (239.80 mm). Only at later unloading stages the value of horizontal displacement gradually reduced until it reached the final value of 105.00 mm after complete unloading.

5 COMPARATIVE COMPUTER SIMULATION

The results of the field investigations were compared with a set of numerical analyses using the finite-element method (FEM). In the analyses an 18.00 m long pile placed in a 40.0 m deep layered soil model composed of three calculation layers was considered. The first (1) 5.0 m thick layer consisted of silt and clay, the second (2) 13.0 m thick layer of silty marly clay and the third (3) one consisted of marly clay-stone. The strength properties of the ground were determined on the basis of the laboratory and field-testing results of additional sound samples (Table 1). The level of ground water included in the model was 3.0 m below the surface. The reinforced concrete of the pile was considered to be linear elastic with an average value of Young's modulus E = 28.0 GPa, a Poisson's ratio $\nu = 0.2$ and a unit weight $\gamma = 25$ kN/m^3.

Table 1. The strength parameters of the soil layers

Layer	γ_{unsat} [kN/m^3]	γ_{sat} [kN/m^3]	k_x [m/day]	k_y [m/day]	E_{50}^{ref} [kN/m^2]	E_{eod}^{ref} [kN/m^2]	E_{ur}^{ref} [kN/m^2]	c_{ref} [kN/m^2]	φ [°]	ψ [°]
1	18.50	18.50	1.0	1.0	2000	2000	6000	16.0	10.0	0.0
2	23.00	23.00	1.0	1.0	100000	100000	300000	1.0	28.0	0.0
3	26.00	26.00	1.0	1.0	1000000	1000000	3000000	90.0	33.0	0.0

The soil half-space can be designed in numerical methods using different material models. In the paper, it was designed by the Hardening-Soil material model with isotropic hardening using Plaxis software – Brinkgrave and Vermeer, 2015). This model considers the nonlinear elastic hyperbolic dependence between the stresses and strains; it enables a consideration of the increasing soil yielding as a function of ground stresses, dilatation and cap yield surface, and is not based on the theory of plasticity (Brinkgrave and Vermeer, 2015). The parameters in the elasto-plastic Hardening-Soil model $E_{oed}^{ref} = E_{50}^{ref}$ and $E_{ur}^{ref} = 3\ E_{50}^{ref}$, where E_{oed}^{ref} is the tangent stiffness for the primary oedometer loading at the reference pressure, and E_{ur}^{ref} is the unloading/reloading stiffness (Brinkgrave and Vermeer, 2015 and 2005).

The Plaxis 3D Tunnel software was used for FEM comparative analysis of the horizontal pile load test. The meshed soil and pile model used for computer simulation is shown in Figure 9.

The measured horizontal displacement of the pile head at load 2450 kN was 239.7 mm. The horizontal displacement for computer simulation using program Plaxis was equal 255.3 mm at failure load equal 1963 kN - the relative shear stresses are shown in Figure 10.

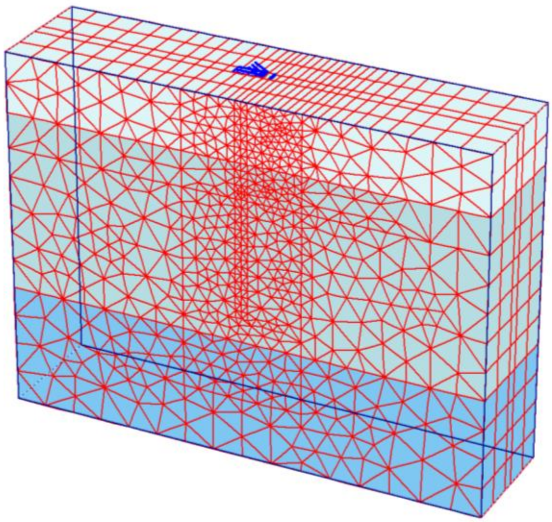

Figure 9. The 3D meshed soil and pile model prepared for simulation of horizontal loading test

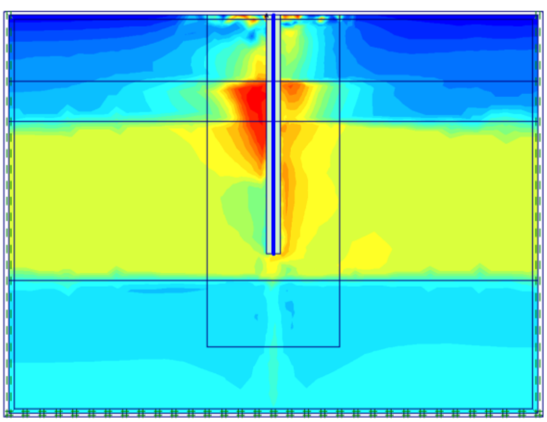

Figure 10. The relative shear stresses of horizontal loading test at failure load equal 1963 kN was equal 255.3 mm

6 CONCLUSIONS

The described improvements of standard measurement technology of static load tests of piles proved themselves as a very reliable. The careful interpretation of measured results could give a lot of important information about the stress state in the pile and in the surrounding soil. The additional information about soil-pile interaction obtained by these investigations could significantly contribute to improvements of the soil model around the test pile and consequently to more accurate results of further computer simulations needed to optimize the foundation design. The presented horizontal loading pile test was a part of the investigation of static pile test loaded vertically as well as horizontally. The results of vertical static load test and further analysis confirmed the possibility of reducing the length of pile from 30.00 m to 18.00 m which leads to important savings in foundation construction without the reduction of safety level.

When the pile was loaded in horizontal direction the load was increased until the pile failure occurred. Because of a large number of measuring points distributed along the pile longitudinal axis it was possible to estimate the position of failure point and the distribution of stresses in the pile and on the contact surface between the pile and soil through all loading stages. On the basis of further analysis of measurement results also the improvement of calculation model can be made.

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