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SOME ASPECTS OF PILE TESTING USING STATIC LOAD TEST (SLT)

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ABSTRACT
The paper presents typical examples of pile load tests with a specific analysis of results, whereby the test methodology relies on existing ASTM standards, own knowledge and experience. The pile tests were conducted using own equipment with licensed hardware and software for the Static Load Test (SLT). The tests have shown some situations that arise when analyzing the bearing capacity of piles. Aspects of application of different equipment and testing methodologies in different situations are indicated. Also, the need to develop a plan for testing the load capacity of piles when it comes to large and significant structures was pointed out.

KEY WORDS: pile, tests, bearing capacity, SLT, counterweight, reactive system

NEKI ASPEKTI ISPITIVANJA NOSIVOSTI ŠIPOVA TESTOM STATIČKOG OPTEREĆENJA (SLT)

REZIME
U radu su prikazani karakteristični primeri ispitivanja nosivosti šipova sa određenom analizom rezultata, pri čemu se metodologija ispitivanja oslanja na postojeće ASTM standarde, sopstvena znanja i iskustva. Ispitivanja šipova su sprovedena primenom sopstvene opreme sa licenciranim hardverima i softverima za test statičkog opterećenja šipa (SLT - *Static Load Test*). Ispitivanjima su prikazane određene situacije koje se pojavljuju kod analize nosivosti šipova. Prikazani su aspekti primene različitih oprema i metodologija ispitivanja u različitim situacijama. Takođe, iskazana je potreba izrade plana ispitivanja nosivosti šipova kada su u pitanju veliki i značajniji objekti.

KLJUČNE REČI: šip, ispitivanje, nosivost, SLT, kontrateret, reaktivni sistem

INTRODUCTION

Testing the load-bearing capacity of piles dates from the time when the use of engineering and technological-constructive approaches began in the analysis of piles of large structures, which were built at the position of the location where a structure is being constructed. However, the question of the relevance of the bearing capacity of an individual pile, obtained by testing, for the analysis of a group of piles still leaves a number of uncertainties and questions. All this increases the level of unreliability in the analysis of the bearing capacity of the piles, even after testing the piles built at the site in question. In addition, the effect of the test is increased if the test is predominantly conducted on test piles, and less on working piles, since piles can thus be brought to a state of limit strength.

A significant contribution to the study of pile load analysis using theoretical and field methods was presented in (Milović, 2018), while in (Ćosić et al, 2019) and (Ćosić et al, 2016), a detailed systematization of pile test methods was presented. An analysis of the bearing capacity of piles constructed by the technology of drilling sand of different compactness was presented in (Rakić et al, 2002) and (Rakić et al, 2010), while in (Barbalić et al, 2007), an examination of the bearing capacity of piles founded on the rock mass was presented. The problem of testing large diameter piles for bridge structures was presented in (Rakić et al, 2014). After conducting the pile load test, it was necessary to determine the ultimate and allowable bearing capacity of the pile, and it was important to correctly determine the safety factor (Šušić, 2002). In (Vukićević et al, 2017), the evaluation of methods for the prediction of the ultimate bearing capacity of individual piles based on the results of the Cone Penetration Test (CPT) and on the analysis of the effective and total stress was presented. The test was conducted on MEGA and Franki piles of different lengths. The results obtained show that the best solution is obtained by applying the Bustamante-Gianeselli method.

A team of engineers and technicians at the Centre of roads and geotechnics of the IMS Institute in Belgrade (Serbia) conducted several hundred SLTs. The bearing capacity tests were carried out for piles of the following structures in Serbia (excerpt): the Mihajlo Pupin bridge in Zemun-Borča, new bridge Beška on the E 75 highway, the bridge near Ostružnica across the Sava river, viaducts for fast railways in Čortanovci, bridge across the DTD canal in Novi Sad, office-residential building – tower Ušće 2, office centre MFC Ušće, wind turbines in Kula, Zagajica, Izbište, Malbunar and Alibunar wind parks, TE Kostolac B fly ash silo, Holcim cement plant in Popovac, thermal electric plant – heating plant (TE-TO) Pančevo, modernization of the Oil Refinery in Pančevo, pulverized coal injection facility of the US Steel blast furnaces in Smederevo, office centre in block 23 in New Belgrade, a large number of structures on the location of Stepa Stepanović Street in Belgrade, Nano centre building in block 39 in New Belgrade, industrial building Nelt in Dobanovci, MPC building in block 43 in New Belgrade, building in dr Ivan Ribar district in New Belgrade, Univerexport building in Novi Sad, new rolling plant Tigar in Pirot, children food factory in Dobanovci, pipeline of the silo complex to the Ćirikovac dump, etc.

STATIC LOAD TEST (SLT)

Static Load Test (SLT) belongs to the High Strain Test (HST) group. In general, there are two variants according to which this test can be performed: the counterweight test and the reactive-pile test (Ćosić et al, 2019). This test analyzes the static mobilized or ultimate bearing capacity of the pile by measuring the pile head settlement by the pile load increments. The test is the most accurate, reliable, and most relevant in determining the bearing capacity of drilled, CFA, and driven piles. The methodology of pile load testing by SLT is defined by ASTM D1143. The Centre of roads and geotechnics of the IMS Institute in Belgrade (Serbia) owns licensed equipment for SLT: presses of the company Prva Petoletka - IMS, software and digital comparators of the Swiss company Sylvac. The comparator accuracy is 0.01mm. With this equipment it is possible to conduct pile bearing capacity testing and to collect data in real time and/or at discrete time intervals. The complete system for SLT consists of: hydraulic presses with capacity of 2x600t and 6x250t, hydraulic system (pump) and engine - aggregates, steel hemispheres, plates, spacers, reference system, dial and digital comparators, hardware system for conversion and acquisition of data, a software system for data processing and visualization, and a surveying system (Leica levelling and bar code staves) for deformation monitoring. An interactive calibration of presses and pumps is carried out before each test. Figure 1 shows the equipment for testing the bearing capacity of piles by SLT: Prva Petoletka - IMS press and hydraulic systems (pumps) - several versions.

Figure 1. Equipment for testing the load-bearing capacity of piles by Static Load Test (SLT): a) Prva petoletka - IMS press, capacity 2x600t, b) Prva petoletka - IMS press, capacity 6x250t, c) hydraulic system (pump) - Version 1, d) hydraulic system (pump) - version 2, e) hydraulic system (pump) - version 3

Figure 2 also shows the pile bearing capacity test equipment using SLT: Sylvac digital comparator, hardware and software system for data acquisition and monitoring, and a geodetic system (Leica levelling and bar code staves). Comparators read and/or store data on pile settlements, while geodetic instruments control pile settlements and adjust the reference beams settlements.

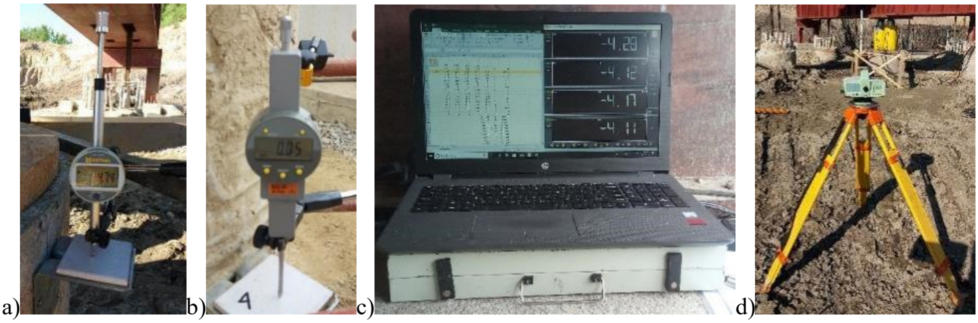

Figure 2. Equipment for pile load testing using SLT: a) digital Sylvac comparator, b) digital comparator, c) hardware and software system for data acquisition and monitoring, d) geodetic system (Leica levelling and bar code staves)

Prior to conducting the test, the complete test system must be properly and carefully fitted, but in different situations a different pile test system must be applied: a counterweight test or a reactive pile test. However, for all types of pile bearing capacity tests using the SLT, comparators should be properly installed and a reference system formed, which will, among other things, be connected to a geodetic system for pile settlement monitoring. Figure 3 shows

Figure 3. a) comparator positioning, b) reference system formed of wooden beams, c) reference system formed of steel lattice R beams, d) specially designed reference system, e) spacing of the pile cap from the concrete slab

the positioning of comparators, the placement of reference systems formed of wooden beams, of steel lattice R beams, or a specially designed reference system.

Also, the positions and layouts of some typical press placement situations and the positioning of comparators within the foundation footing are presented, and the aspect of the spacing of the pile cap from the concrete slab is particularly emphasized.

The bearing capacity tests of piles using the SLT with a counterweight are shown in Figure 4: The Mihajlo Pupin Bridge in Zemun-Borča in Serbia (counterweight formed by reinforced concrete slabs) and Malibunar wind farm in Serbia (counterweight formed by reinforced concrete blocks). In the first case, the counterweight is stacked on reinforced concrete supports that are orthogonally mutually prestressed, while in the second case the counterweight is stacked on steel supports.

a) b)

Figure 4. SLT - counterweight: a) The Mihajlo Pupin bridge in Zemun-Borca, Serbia (counterweight formed of reinforced concrete slabs), b) wind farm Malibunar in Serbia (counterweight formed of reinforced concrete blocks)

The bearing capacity tests of piles using the SLT with a reactive system are shown in Figure 5: the bridge at Ostružnica across the Sava river in Serbia (a reactive system formed of a reinforced concrete beam and of four reinforced concrete piles) and an office-commercial building-tower Ušće in Serbia (a reactive system formed from reinforced concrete XX supports and six reinforced concrete piles). In this case, temporary reactive reinforced concrete systems were formed, which were removed after the tests.

Applications of steel beams for the formation of a reactive structural system for testing the bearing capacity of piles using the SLT are shown in Figure 6: the bridge on corridor XI

(Surčin-Obrenovac) in Serbia (reactive system formed of a welded steel beams and four reinforced concrete piles), the fly ash silo at TE Kostolac B in Serbia (a reactive system formed by additionally reinforced dual steel beams and two reinforced concrete piles) and fast railway viaducts in Čortanovci, Serbia (a reactive system formed by double-crossed steel sections and four reinforced concrete piles). Also, temporary (assembly) reactive steel systems were applied here, which are removed after testing and but also used for further testing.

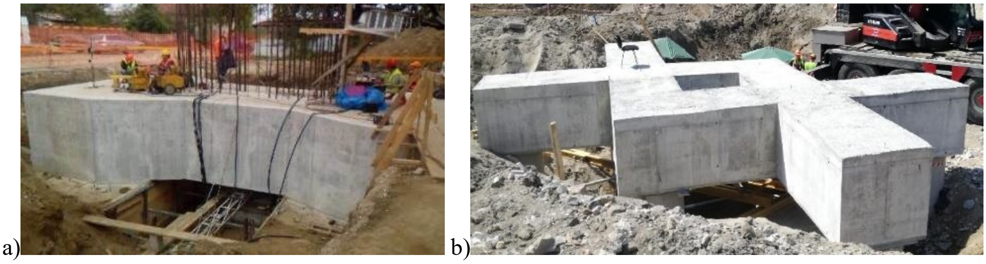

Figure 5. SLT - reactive system: a) bridge at Ostružnica across the Sava river in Serbia (reactive system formed of reinforced concrete beam and of four reinforced concrete piles), b) office-commercial building-tower Ušće in Serbia (reactive system formed of reinforced concrete XX supports and six reinforced concrete piles)

Figure 6. SLT - reactive system: a) bridge on corridor XI (Surčin-Obrenovac) in Serbia (reactive system formed from welded steel beam and four reinforced concrete piles), b) fly ash silo at TE Kostolac B in Serbia (reactive system formed of additionally reinforced dual steel beams and two reinforced concrete piles), c) fast railway viaducts in Čortanovci, Serbia (reactive system formed of double-crossed steel sections and four reinforced concrete piles)

Compared to the provisional pile load test systems (counterweight and reactive system) shown above, Figure 7 shows the structural reactive system: fast railway viaducts in

Čortanovci, Serbia (a reactive system formed from reinforced concrete footing – top foundation slab for piles) and MFC Ušće Business centre in Serbia (a reactive system formed by presses pushing against the supporting structure). After the tests have been carried out, structural reactive systems are used as part of the foundation and the supporting structure.

After conducting the SLT, the test load curve (load-settlement) obtained by measuring the settlement of comparators and applying the load through the press pistons, is further corrected to include the settlement of the reference beams. Figure 8 shows the test load curves for: the working pile of a structure in Pančevo, Serbia (two load-settlement cycles) and the test pile of the bridge at the Belgrade ring road in Serbia (three load-settlement cycles).

a) b)

Figure 7. SLT - reactive system: a) viaducts for fast railways in Čortanovci, Serbia (reactive system formed from reinforced concrete foot – top foundation slab for piles), b) MFC Ušće business centre in Serbia (reactive system formed by presses pushing against the supporting structure)

Generally speaking, two groups of behaviors of pile interacting with soil can be distinguished:

– the test load curve is of such character where there is a linear and nonlinear part, but the tangent stiffness in the nonlinear part does not decrease considerably with increasing deformations - the bearing capacity criterion is more relevant (Figure 8a),
– the test load curve is of such a character where there is a clearly pronounced nonlinear part and early nonlinearity develops with significant plastic deformation - the serviceability criterion is more relevant (Figure 8b).

a) b)

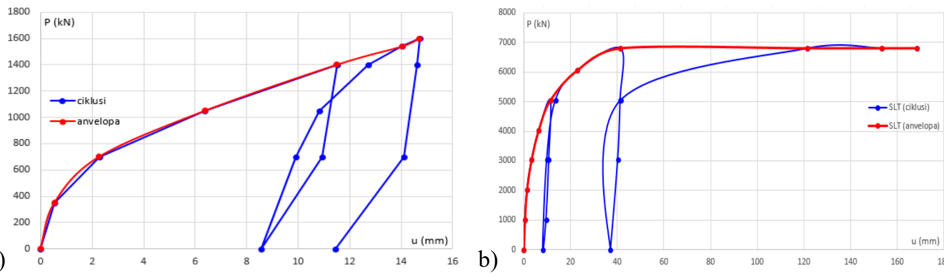

Figure 8. Test load curves - SLT: a) working pile of a structure in Pančevo, Serbia (two load-settlement cycles and envelope), b) test pile of a bridge on the Belgrade ring road (three load-settlement cycles and envelope)

In order to determine the ultimate bearing capacity of the pile after conducting a SLT, extrapolation by the Chin-Kondner method (Chin, 1970) is performed for the obtained test load curve:

$$P = \frac{u}{c_1 u + c_2} \tag{1}$$

where P is the force, u settlement, C_1 and C_2 curve coefficients, or using the Hansen method (Hansen, 1961):

$$P = \frac{\sqrt{u}}{c_1 u + c_2} \tag{2}$$

or using the Decourt method (Decourt, 1996):

$$P = \frac{c_2 u}{1 - c_1 u} \tag{3}$$

The extrapolation of the test load curve using the rational function is conducted using the Levenberg-Marquardt algorithm (Ćosić et al, 2020). The rational function represents the quotient of two polynomials of different degrees n and m in the following form:

$$P = \frac{a_0 + a_1 u + \cdots + a_n u^n}{b_0 + b_1 u + \cdots + b_m u^m} \tag{4}$$

where $a_0, \ldots a_n$, $b_0, \ldots b_n$ are the coefficients of the polynomial. Figure 9 shows the test load curves extrapolated by the previously presented methods.

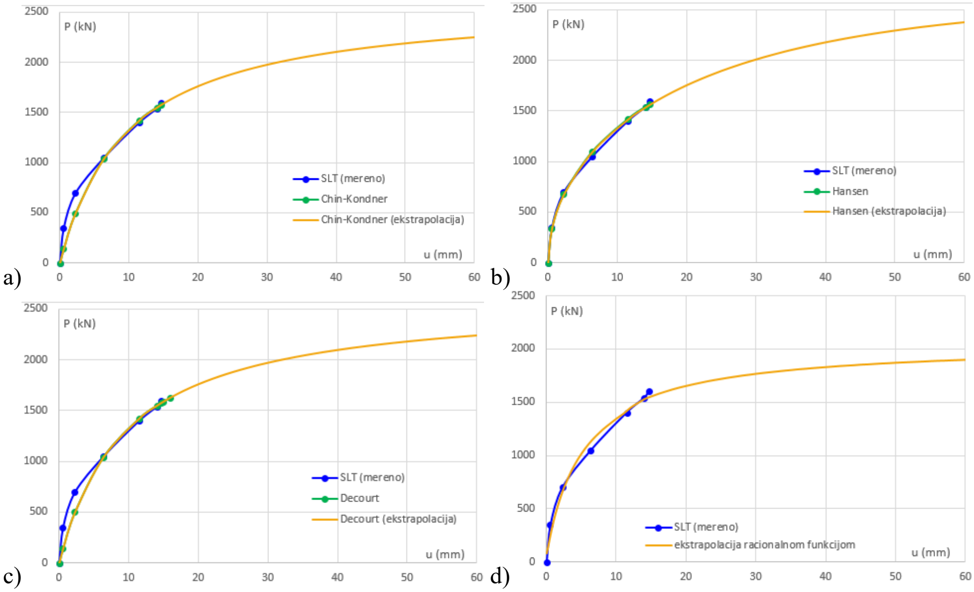

Figure 9. Test load curves, for the SLT of the service pile of the structure in Pančevo in Serbia, obtained by extrapolation using the following methods: a) Chin-Kondner, b) Hansen, c) Decourt, d) rational function

CONCLUSION

The pile load test can be methodologically presented in several stages: test preparation, test equipment control, in-situ pile test on the construction site, analysis and decision making during testing, analysis, interpretation and presentation of test results, ultimate strength analysis, additional numerical bearing capacity analyses, making a decision on pile bearing capacity and writing a pile bearing capacity report. The biggest problem arises when all the piles of the building are built, and pile load tests are subsequently required, as this creates limited space for corrections, both at the structural level and at the level of the dynamic building construction plan. Also, in a large number of cases, in the process of interpreting the test results presented in the reports for a single pile, by the contracting authority, it is concluded that a particular entity or complete foundations exhibit a satisfactory bearing capacity. The question of the representativeness of the number and position of piles for testing is a particular issue, which should be defined already at the level of the pile test plan. On the other hand, the verification of the bearing capacity of certain segments or of the complete foundation is a process that goes beyond the very problem of testing the bearing capacity of piles. In this regard, when analyzing the soil-structure interaction of large and significant structures, there should be special expert consulting firms dealing with the soil-structure interaction problem whose role would be to coordinate the collaboration of the designer, contractor and examiner.

The problem of pile load testing is multidisciplinary in nature, since it requires the integration of knowledge and experience in the fields of civil engineering, geology, geotechnics, signal analysis and processing, software and hardware engineering, so there is a constant need for harmonisation of almost all testing aspects. The issues of theory and signal processing, and hardware and software engineering are particularly sensitive, because of the constant improvements in modern information technologies. In this regard, the civil and geotechnical engineers are constantly faced with the question of improvement in this field, where this paper can be one of the informative and educational starting points, and in which, beside the standardised pile testing procedures, we have defined and matched personal experiences and knowledge from a number of different pile testing methods.

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