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SOME ASPECTS OF PILE TESTING USING DYNAMIC LOAD TEST (DLT)

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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 Dynamic Load Test (DLT). The tests have shown the correct and problematic 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, DLT, signal matching

NEKI ASPEKTI ISPITIVANJA NOSIVOSTI ŠIPOVA TESTOM DINAMIČKOG OPTEREĆENJA (DLT)

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 dinamičkog opterećenja šipa (DLT - *Dynamic Load Test*). Ispitivanjima su prikazane korektne i problematične situacije koje se pojavljuju kod analize nosivosti šipova. Ukazano je na aspekte primene različitih oprema i metodologija ispitivanja u različitim situacijama. Takođe, ukazano je na potrebu izrade plana ispitivanja nosivosti šipova kada su u pitanju veliki i značajniji objekti.

KLJUČNE REČI: šip, ispitivanje, nosivost, DLT, kompatibilizacija signala

INTRODUCTION

Over time, various pile testing techniques were developed, and the development of electronic instruments, hardware components and software engineering enabled the digitization and monitoring of pile behavior in real time and subsequent data processing. In many cases, the geological conditions of the site in question, where the structure is being built, can be significantly non-uniform in terms of the physical-mechanical characteristics of the soil and the stratification of soil layers by depth. Solving such complex problems usually boils down to a decrease in the safety factor during design and after testing, but also to an increase in the number of piles tested at the location. A special role is played by the design of the pile test, still in the design phase of the structure and piles, with particular regard to the types of tests, selection and position of piles to be tested, the amount of tests to be carried out on test and/or working piles, etc.

Depending on the assessment of the parameters present in the pile load analysis, solutions with a lower or higher degree of reliability are obtained (Šušić et al, 2014). On the other hand, simultaneously with the pile testing, analytical-numerical procedures for pile bearing capacity were carried out (Ćosić et al, 2012), (Ćosić et al, 2016), (Ćosić et al, 2018). In (Ivšić et al, 2013), the bearing capacity and settlement of piles constructed by the soft-soil drilling technology were analyzed, showing that empirical methods of load-bearing estimation from geotechnical soil parameters introduced a number of specific simplifications, leaving out some elements of the complex soil-pile interaction. The results of field testing of piles are, in fact, the cumulative consequence of the complex overall conditions at the soil-pile contact.

A team of engineers and technicians at the Centre of roads and geotechnics of the IMS Institute in Belgrade (Serbia) conducted several hundred DLTs. The bearing capacity tests were carried out for piles of the following structures in Serbia (excerpt): the Belgrade ring-road bridges, viaducts on the E 70/E 75 highway, bridges on Corridor X and XI, access road to the Ada bridge, office-residential building – tower Ušće 2, office centre MFC Ušće, wind turbines in Kula, Zagajica, Izbište, Malbunar and Alibunar wind parks, shoreline for the Belgrade Waterfront project, Belgrade centre - Prokop railway station, thermal electric plant – heating plant (TE-TO) Pančevo, modernization of the Oil Refinery in Pančevo, office centre in block 23 in New Belgrade, new building of German embassy, office complex Airport City, plateau on Slavija square, shopping complexes Lidl in Belgrade, office-residential complex Central Garden in Belgrade, hotel Mona in Belgrade, hotel complex in Lukovska Banja, hotel on Rtanj mountain, 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, Aviv Park facilities in Belgrade and Zrenjanin, children food factory in Dobanovci, De Heus animal fodder in Šabac, manufacturing building Mitas in Ruma, bridges on the express road Gradsko-Prilep (Macedonia), etc.

DYNAMIC LOAD TEST (DLT)

Dynamic Load Test (DLT) also belongs to the High Strain Test (HST) group. Since there are several variants of equipment and methods of the dynamic load tests, this paper presents tests conducted with its own lifting system. In most cases, the test determines the mobilized static bearing capacity of the pile, which proves the maximum design bearing capacity of the pile. Using this test, the bearing capacity of drilled and CFA piles is tested, while with some variation, driven piles are also tested. The methodology of pile load testing using the DLT is defined by ASTM D4945. The Centre of roads and geotechnics of the IMS Institute in Belgrade (Serbia) possesses its own original system and licensed equipment for DLT: software and hardware from the Dutch company Profound. With this equipment it is possible to conduct pile bearing capacity testing and to collect data in real time and perform the subsequent data processing. The complete DLT system consists of: a steel supporting structure that is mounted and connected to a pile head extension, modular weights, a hydraulic system for lifting weights to a certain height, a weight stop system (braking system), motor with an electrical power generator, sensors (accelerometers and strain meters), a hardware system for data conversion and acquisition, a software system for data processing and visualization, and a surveying system (Leica levelling and bar code staves) for deformation monitoring. The strain meter has a measurement range of -2000 micro-strain to +2000 micro-strain and natural frequencies greater than 2kHz (https://profound.nl). A piezo-resistive accelerometer with a measurement range of -5000g to + 5000g and a resonant frequency greater than 8kHz is used to measure accelerations. Figure 1 shows the pile bearing capacity testing equipment using the DLT of the Centre of roads and geotechnics of the IMS Institute in Belgrade (Serbia).

Figure 1. DLT equipment of the Centre of roads and geotechnics of the IMS Institute in Belgrade (Serbia)

Figure 2 also shows the pile bearing capacity test equipment using the DLT: hardware, signal processing system, sensors, connectors and supporting cables from the Dutch company Profound. Two software packages are used for pile bearing capacity analysis: PDA-DLT monitoring software for in situ DLT pile testing and DLT-WAVE signal processing software, where the signal of the nonlinear numerical hysteresis model of the soil-pile interaction is matched with the signal obtained by in-situ DLT testing.

Figure 2. Pile bearing capacity testing equipment using DLT of the Dutch company Profound (https://profound.nl)

Prior to carrying out the test, it is necessary to form a pile head extension or this extension is constructed as an integral part of the pile head when implementing the pile construction technology. Figure 3 and 4 show piles (pile head extensions) prepared for the DLT: adequate preparation (background shows the trimmed pile head on which the pile head extension is being built), adequate preparation (further elimination of the connection of the head pile extension and the concrete slab), inadequate preparation (pile head extension is set eccentrically with respect to pile head, while the pile head and the pile head extension connection is improperly constructed), inadequate preparation (pile head extension is geometrically incorrectly constructed and the pile head is inadequately trimmed before the construction of the pile head extension), adequate preparation (pile head extension formed

a)  b)  c)  d) 

Figure 3. Piles (pile head extensions) prepared for the DLT: a) adequate preparation, b) adequate preparation, c) inadequate preparation, d) inadequate preparation

a) b) c)

Figure 4. a) adequate preparation, b) partially adequate preparation, c) partially adequate preparation

by virtually excavating the pile - without additional concreting), partially adequate preparation (pile head extension is prismatic in shape, while the pile has a circular cross section), partially adequate preparation (pile head extension is prismatic in shape and is eccentrically positioned with respect to the pile head but the sensors are positioned on the pile head).

Depending on the value of the maximum design pile bearing capacity and the permitted settlement, a test plan is made prior to conducting the test, in which the appropriate weight of the pile and the preliminary fall height are defined. Given the weight modularity option and the ability to raise it to the required heights, it is possible to create appropriate combinations of the weights and their heights for each DLT test. This gives a spectrum of pile bearing capacity values that can be realized by testing using the previous set-up of equipment. Figures 5 and 6 show the options for setting the equipment for DLT in Serbia: Sava Promenade, Malibunar wind farm, Aviv Park in Belgrade, access road for the Ada bridge,

a) b) c) d)

Figure 5. DLT – equipment set for the tests in Serbia: a) Sava Promenade, b) Malibunar wind farm, c) Aviv Park in Belgrade, d) access road for the Ada bridge

office-commercial building-tower Ušće 2, Gradsko-Prilep express road bridges in Macedonia, bridges on corridors X and XI and viaducts on the E 70/E 75 highway.

In certain situations, when additional signal control is required during in-situ DLT testing and pile bearing capacity analysis and for significant structures, the DLT testing is performed using two equipment sets.

a) 
b) 
c) 
d) 

Figure 6. DLT – equipment set for the tests in Serbia: a) office-commercial building-tower Ušće 2, b) Gradsko-Prilep express road bridges in Macedonia, c) bridges on corridors X and XI, d) viaducts on the E 70/E 75 highway

Figure 7 shows a typical example of pile bearing capacity testing using the DLT with two equipment (simultaneous acquisition and signal processing). In total, 4 sensors were installed at the same cross-section level of the pile, so that 8 signals (4 acceleration signals and 4 strain signals) were obtained, which are processed in real time, but also analyzed subsequently.

Figure 7. Pile bearing capacity testing using the DLT with two equipment (simultaneous acquisition and signal processing - 4 sensors and 8 signals)

The mathematical formulation of the DLT problem is based on the theories: rigid-body dynamics, wave theory, method of characteristics, nonlinear theory, dynamics of structures, soil-structure interaction (SSI) and theory and signal processing (Ćosić et al, 2019). During the dynamic load test applied to the pile head extension, due to the free fall of the corresponding weight mass *m* and from the appropriate height *h*, the impact energy is transferred and deformation (settlement) of the pile occurs, whereby the allowable compression and tension stresses in the pile are controlled. Figure 8 shows the pile deformation analysis of the DLT.

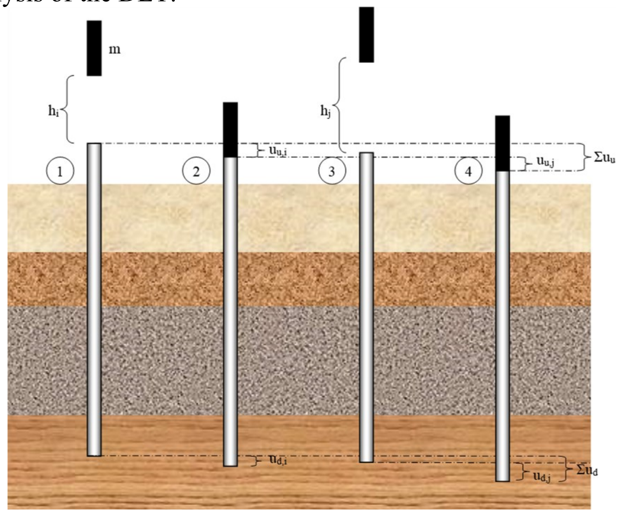

Figure 8. Analysis of pile deformation during the DLT

Using the basic principles of mechanics, through the law of energy conservation, the formulation of the DLT pile problem can be derived by establishing the equivalence ratio of the potential energy E_p (the weight was raised to the height h) and the kinetic energy E_k (the weight fell freely on the extension of the pile head). In this regard, four independent situations were considered:

- 1. the weight is raised at the height h_i and the pile is not loaded,
- 2. the weight freely fell from the height h_i on the pile head causing deformations $u_{u,i}$,
- 3. the weight is raised at the height h_j and the pile is not loaded, whereby $h_j > h_i$,
- 4. the weight freely fell from the height h_j on the pile head causing deformations $u_{u,j}$.

In the first situation, the potential $E_{p,0}$ and kinetic $E_{k,0}$ energy are Barger, 1973):

$$E_{p,0} = \int_{y=0}^{y=h_i} mg\,dy = mgh_i \qquad E_{k,0} = 0, \tag{1}$$

where g is gravity acceleration. In the second situation the potential $E_{p,i}$ and kinetic $E_{k,i}$ energy are:

$$E_{p,i} = 0 \qquad E_{k,i} = \int_0^v d\left(\frac{mv^2}{2}\right) = \frac{mv^2}{2}, \tag{2}$$

where v is the velocity of the weight falling freely from the height h_i, and it is determined according to:

$$v = \sqrt{2gh_i}. \tag{3}$$

On the basis of the measured strains $\varepsilon(t)$, concrete modulus of elasticity E and surface area of the cross-section of the A pile, the $F(t)$ force is calculated according to:

$$F(t) = \varepsilon(t)EA. \tag{4}$$

On the other hand, based on the measured accelerations, using the firs numerical integration, the velocity $v(t)$ is obtained and the force $F(t)$ is calculated according to:

$$F(t) = v(t)\frac{EA}{c} = v(t)Z, \tag{5}$$

Where c is the velocity of wave propagation in concrete, Z is the pile impedance (depending on the material characteristics and geometry of the pile cross-section). The total value of static R_{sta} and dynamic R_{dyn} resistance R_{tot} is determined from the sum of the downward traveling wave $F^{\downarrow}$ and the upward traveling wave $F^{\uparrow}$ (PDA-DLT software help theory):

$$R_{tot} = F^{\downarrow}(t_{max}) + F^{\uparrow}\left(t_{max} + \frac{2L}{c}\right), \tag{6}$$

Where L is the pile length, while in the general case the forces obtained from the waves are calculated according to:

$$F(t)^{\downarrow} = 0.5\left(F(t) + Zv(t)^{\downarrow}\right) \quad F(t)^{\uparrow} = 0.5\left(F(t) - Zv(t)^{\uparrow}\right). \tag{7}$$

Monitoring of all the relevant parameters of pile behavior is performed by implementing the variation diagram: acceleration over time for each separate sensor $a(t)$, velocity over time for each separate sensor $v(t)$, displacements over time for each separate sensor $u(t)$, total average accelerations over time $a_{ave}(t)$, total average velocities over time $v_{ave}(t)$, total average displacements over time $u_{ave}(t)$, force over time (from accelerations and strains) for each separate sensor $F(t)$, total average forces in time $F_{ave}(t)$, force of downward wave in the pile $F_d(t)$, force of the upward wave in the pile $F_u(t)$ and kinetic energy in time $E_k(t)$. The determination of the bearing capacity of the pile, from the results of in-situ DLT, is carried out using an indirect method. Indirectly, the bearing capacity of the pile is determined by a signal matching process, which is an iterative process of finding static and dynamic soil parameters in order to obtain a computational signal that best matches the measured signal. More specifically, it matches the signal of the nonlinear numerical model of the soil-pile interaction with the measured signal from the in-situ DLT. The numerical pile interaction model with soil is a continuous mathematical model with continuously distributed masses and modelled stiffness. Measured signal refers to an upward wave, that is, a wave moving upwards from the toe, because it basically carries data about the resistance of the ground. Diagrams of variation of forces over time, diagrams of variations of upward traveling wave force over time and diagrams of force-settlement, obtained by in-situ DLT by measuring strains and accelerations and subsequent calculation for structures in Serbia, are shown in Figures 9, 10 and 11, respectively: service pile of viaducts on the E

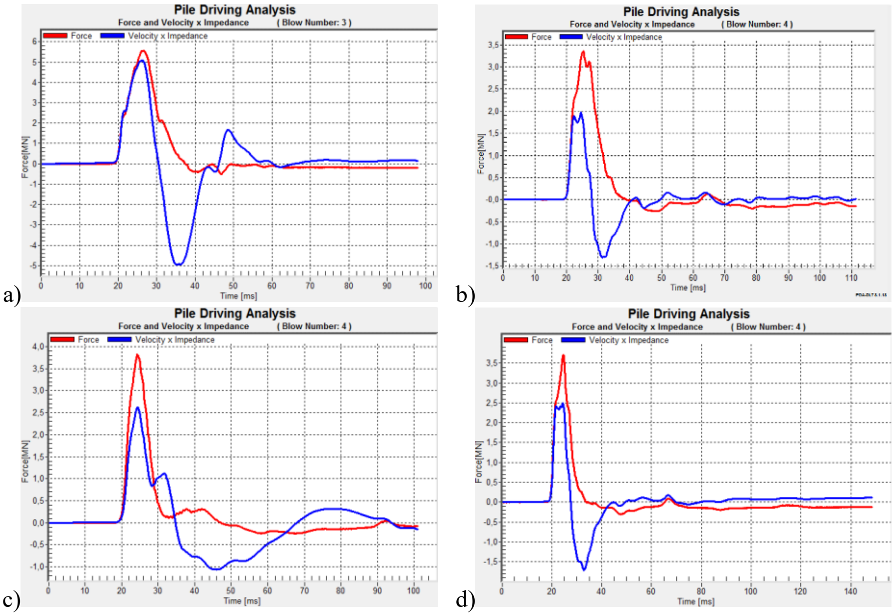

Figure 9. Diagrams of variation of forces over time obtained by in-situ DLT by measuring strains and accelerations and by subsequent calculation for structures in Serbia: a), b), c), d)

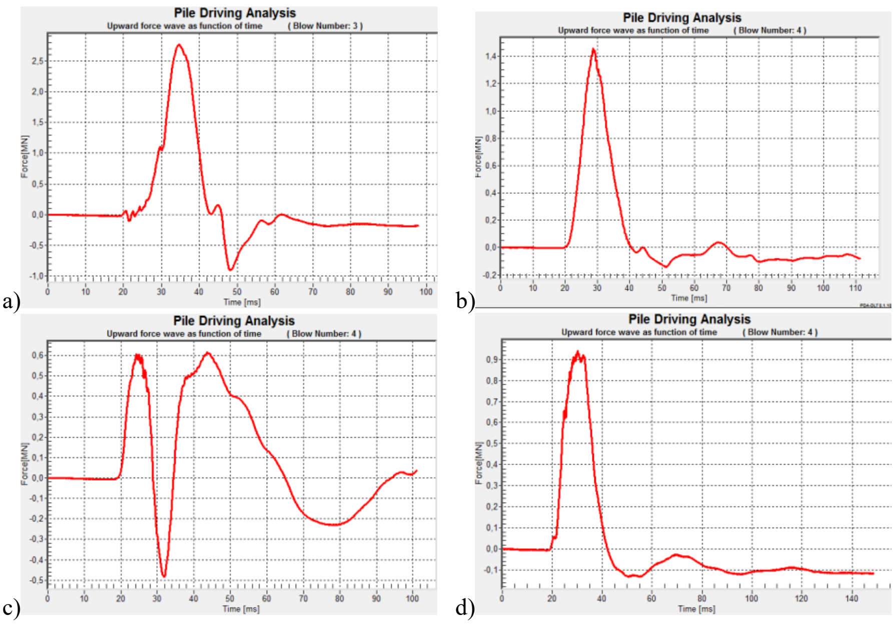

Figure 10. Diagrams of variations of upward traveling wave force over time, obtained by in-situ DLT by measuring strains and accelerations and by subsequent calculation for structures in Serbia: a), b), c), d)

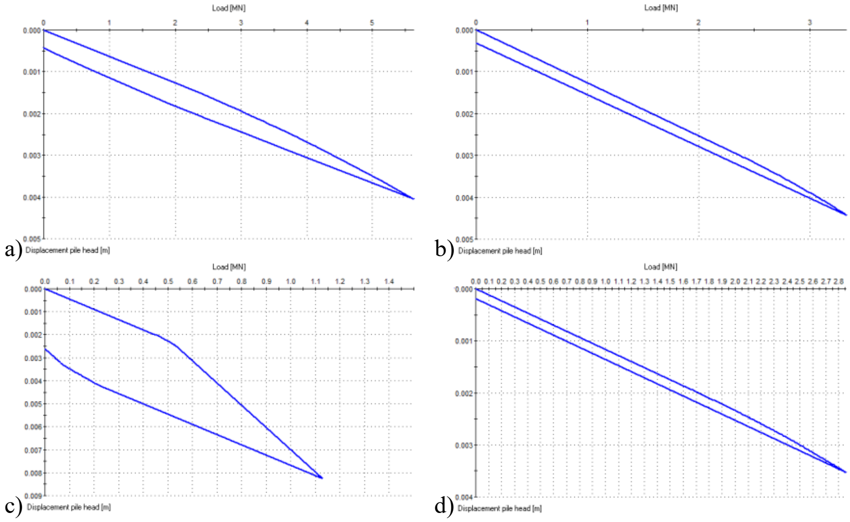

Figure 11. Diagrams of force-settlement: a), b), c), d)

70/E 75 highway, service pile of a residential building in Belgrade, test pile of an office building in New Belgrade and the service pile of the wind turbine in the Kovačica wind farm. These diagrams were calculated by signal matching of upward traveling wave force of nonlinear numerical models of soil-pile interaction with the signals obtained by in-situ DLT of piles in the field.

CONCLUSION

Regarding the cost of testing, DLT is most commonly used recently to test the vertical bearing capacity of piles. Also, to a large extent, tests are conducted on service piles, and increasingly less on test piles. In addition, the principle of minimizing the amount of testing is applied, which directly reduces the levels of load-bearing reliability, stability, and serviceability of certain segments or of the entire structural foundation system. When it comes to a large number of piles of a building, it is more reliable to make a test plan before building the piles.

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