Originalni naučni rad
UDK: 624.154.8

ANALYSIS OF REDISTRIBUTION OF THE PILE SHAFT-BASE LOAD USING THE DYNAMIC LOAD TEST (DLT)

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ABSTRACT
The paper analyses transmission and redistribution of the load from the pile on the soil, with a special focus on these effects regarding the shaft and base of the pile. The test was conducted using the dynamic load test (DLT) by incrementally increasing the kinetic energy of the drop weight impact in several drops. The results of in–situ DLTs are presented and after the performed signal matching for every impact of the drop weight. The testing and appropriate numerical analyses determined the mechanism of redistribution of the shaft-base load of the pile up to the ultimate bearing capacity, whereby there occurs a reduction in the transmission of the load via the shaft and an increase in the transmission of the load via the base.

KEY WORDS: pile, shaft, base–toe, bearing capacity, testing, DLT

ANALIZA PRERASPODELE OPTEREĆENJA OMOTAČ–BAZA ŠIPA TESTOM DINAMIČKOG OPTEREĆENJA (DLT)

REZIME
U radu je analizirano prenošenje i preraspodela opterećenja sa šipa na tlo, sa posebnim ovrtom na ove efekte kod omotača i baze šipa. Ispitivanje je sprovedeno testom dinamičkog opterećenja (DLT) inkrementalno povećavajući kinetičku energiju udara tega kroz nekoliko udaraca. Prikazani su rezultati *in–situ* DLT ispitivanja i nakon sprovednih kompatibilizacija signala za svaki udarac tega. Ispitivanjem i odgovarajućim numeričkim analizama utvrđen je mehanizam preraspodele opterećenja omotač–baza šipa do granične nosivosti, pri čemu nastupa redukcija u prenošenju opterećenja omotačem i povećanje u prenošenju opterećenja bazom.

KLJUČNE REČI: šip, omotač, baza, nosivost, ispitivanje, DLT

INTRODUCTION

The pile bearing capacity calculation is performed using analytical and numerical methods based on the parameters of laboratory soil tests, analytical methods based on the in–situ soil penetration tests, but also using the laboratory model testing of pile-soil interaction. However, the most reliable results are obtained by implementing the in–situ test of the bearing capacity of piles built in the soil using the static load test (SLT – Static Load Test) and dynamic load test (DLT – Dynamic Load Test). DLT is more extensively used, considering the short time required to perform them and low risk during the test as well as the considerable degree of reliability of the obtained results. In addition to the pile bearing capacity analysis, DLT can provide a considerably higher number of parameters and corresponding results of pile behavior, in comparison to the result obtained by using SLT. Some of these results are the possible analyses of transmission and redistribution of load from the pile on the soil, with a special focus of the effects regarding the pile shaft and base. The research (El-Reedy, 2012) showed the models of load distribution of the shaft and base of the pile, but in a cumulative form. In case of a pile founded in clay, the ultimate bearing capacity and shaft bearing capacity are relatively rapidly reached, with a further relaxation of bearing capacity with the increasing settlement, especially in terms of the load transmission via the shaft. In case of a pile founded in sand, the ultimate bearing capacity reaches the constant value with mild increase of values, without relaxation of bearing capacity with the increase of settlement. In the paper (Wrana, 2015), briefly, were presented the models of load transmission via the shaft and the base, in the cases when the load is dominantly transmitted: via the shaft and where there is no redistribution of the shaft-base load, and via the base and where there is a redistribution of the shaft-base load. The experimental test on the pile model in the laboratory shows the load redistribution along the shaft and in the base to the ultimate bearing capacity (Żarkiewicz et al., 2015) (Żarkiewicz, 2018). The paper (Nanda et al., 2014) considered the load transmission models via the shaft of the pile, using *t–z* curves, with the maximum shear stress reached, after which: follows the residual shear stress plateau (characteristic for clays), and there is no shear stress reduction (characteristic for sand). Test results are compared to the field tests, whereby for the proposed non-linear soil behavior model are obtained the results which are in good agreement with the measuring. Using a reverse numerical analysis, based on the test load curve of the pile in SLT and by modeling the mechanism of load transmission along the pile shaft using *t–z* function, the analysis yielded the model of load distribution between the shaft and the base of the pile. (Fellenius, 2018). SLT and the research by calculation of the pile shows the load distribution via the shaft and base, where the aspect of the occurrence of reduction in transmission of the load via the shaft and the consequences for the pile settlement is particularly emphasized (Żarkiewicz, 2019).

To the knowledge of the authors of the paper, until now there were no tests analyzing the impact of the load redistribution and the redistribution mechanism between the shaft and base of the pile using DLT. The research of this topic is presented in the further text. The paper represents the identification and diagnostics of the problem of redistribution of the load between the shaft and base of the pile, and the following paper will deal with the analysis of the development of the load redistribution between the shaft and base of the pile.

PILE DLT METHODOLOGY

Dynamic Load Test (DLT) belongs to the high strain test group and it based on determining the mobilized force in the pile (mobilized load-bearing capacity) during the dynamic external excitation. DLT is performed by letting the drop weight fall from a specific height, whereby, due to the impact of the drop weight on the pile head, a dynamic excitation in pile is caused. The control system of a DLT consists of: steel supporting structure fitted and connected to the pile head extension, modular drop weight, hydraulic system for lifting of drop weights to a specific height, arresting system (braking system) of the drop weight at a specific height, motor with a power generator, and wooden blocks. The electronic equipment (hardware and software system) for DLT of the pile consists of: sensors with integrated accelerometers and strain gauges, devices (conditioner) for data acquisition and signal digitalization, portable computers for test control, software for monitoring and processing signals during the test, software for the detailed calculation of the pile bearing capacity and the digital leveling for surveying of pile settlement.

DLT was conducted on a pile in Vojvodina. In figure 1 are shown the CPT penetrations and defined the soil types by layers, determined based on the Robertson classification.

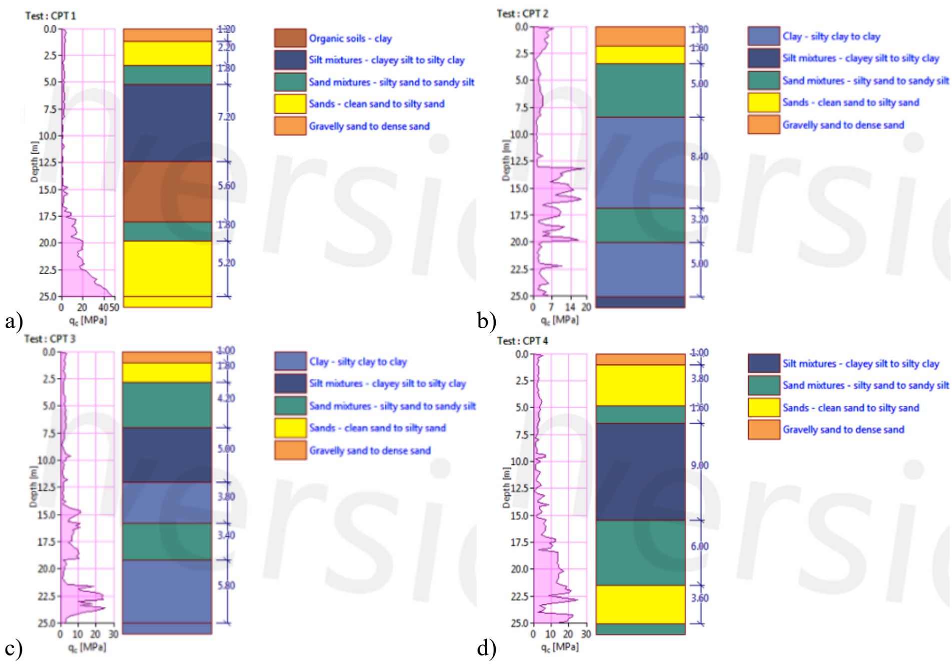

Figure 1. CPT penetrations and soil types defined by layers, determined on the basis of the Robertson classification

The tested pile, in terms of construction technology is a non-reinforced SDP (Soil Displacement Pile) having diameter of Ø520 mm and length of 14m. For the testing purpose, a pile extension 1.8m long was built, on which the sensors were mounted. The drop weight used had the weight of 2.5t. Figure 2 shows the fitted and set mechanical and electronic equipment for DLT of the pile.

Figure 2. Equipment for in–situ DLT of the pile

The term – testing the mobilized bearing capacity of the pile comprises determining the intensity of reactive forces of the pile in cumulative (total) form (by the shaft and the base) and the reactive forces of the pile in the component (independent) form (by the shaft and the base). Determining the bearing capacity, from the results of in–situ DLTs, is performed by implementing the indirect method. In an indirect way, the bearing capacity is determined by the signal matching procedure, which represents an iterative procedure of finding the static and dynamic soil parameters with the goal of obtaining a calculated signal which best matches the measured signal. The analysis of the quality of the conducted signal matching procedure is carried out considering the percentage departures of the matched in–situ measured signal in the following domains: along the shaft, wave entering the base, in the base, leaving the base and cumulative.

PILE DLT RESULTS

Dynamic pile load was conducted using the free fall of the drop weight, whereby each following weight drop had the incrementally increased height. Figure 3 shows the diagrams of force variation in time obtained by in–situ DLT by measuring strains and accelerations (fresh signals) for different heights of drop weight h. Accelerometers measure accelerations, and forces are calculated based on the product of velocities (numerical integration) and impedance. Strain gauges measure strains, and the forces are calculated based on the product of the modulus of elasticity of concrete, cross section area and strains. Using the signal matching procedure of the return wave of the force, nonlinear numerical pile-soil interaction and the measured results yielded the diagrams of pile settlement in the function of the mobilized force in the pile for each drop weight impact.

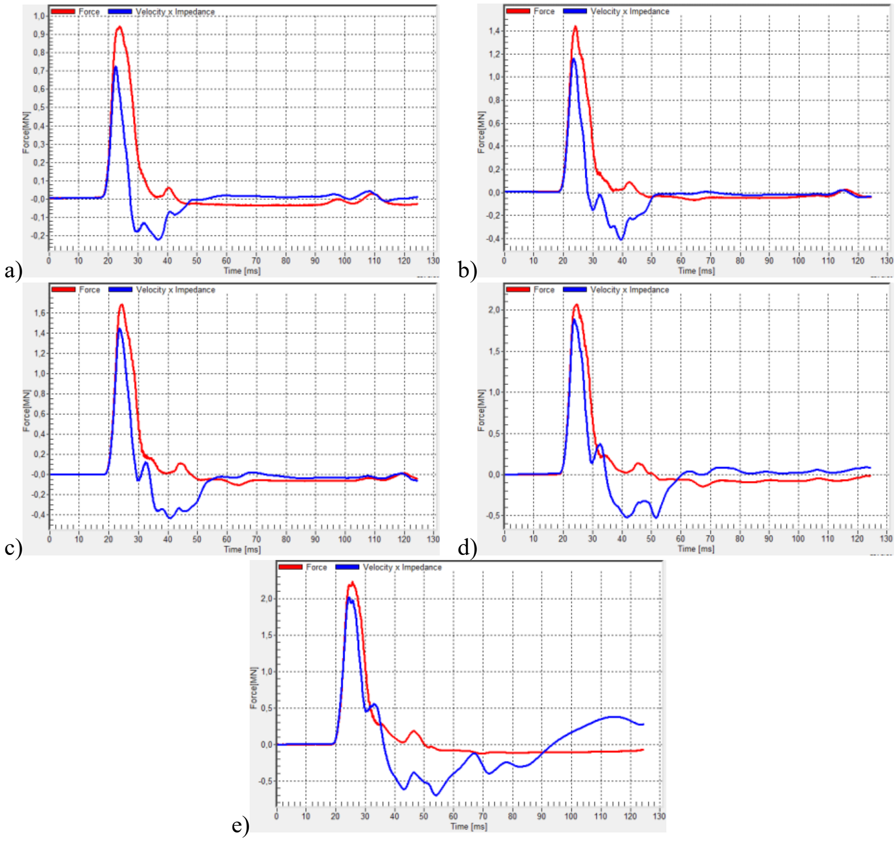

Figure 3. Diagram of force variation in time obtained by in–situ DLT measuring of strains and accelerations (fresh signals): a) h=0.2m, b) h=0.4m, c) h=0.6m, d) h=1m, e) h=1.4m

The analysis of these diagrams identified that the shaft resistance is dominant for first two impacts, while for the remaining two impacts the pile base resistance is dominant. Table 1 shows the values: kinetic energy E_k, driving force R_{dr}, realized plastic settlement s_p, realized elastic–plastic settlement s_{ep}, total mobilized static force R_u from DLT, mobilized static force of the shaft R_s from DLT and mobilized static force of the base R_b from DLT.

Table 1. Values obtained by in–situ DLT and calculation of mobilized static forces of the pile

h	E_k	R_{dr}	s_p	s_{ep}	R_u	R_s	R_b
(m)	(kNm)	(kN)	(mm)	(mm)	(kN)	(kN)	(kN)
0.2	1.9	998	0.62	1.95	509	459	50
0.4	3.5	1383	0.76	3.3	655	508	147
0.6	5.8	1646	1.42	4.8	677	403	274
1	9.9	1956	2.17	6.2	710	198	512
1.4	13.1	2075	2.83	8.7	759	143	617

Figure 4 presents force-settlement diagrams obtained by in–situ DLT and calculation of mobilized static forces using signal matching. Diagrams are presented so that each starts from the zero. This was done so that the difference between the forces and settlements obtained by testing (different heights of drop weight) could be visually perceived.

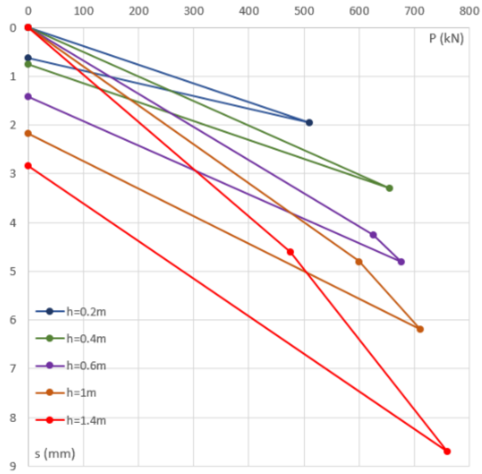

Figure 4. Force-settlement diagrams obtained by in–situ DLT and by calculation

Figure 5 shows mobilized static force in component and cumulative forms obtained by in–situ DLT and by calculation.

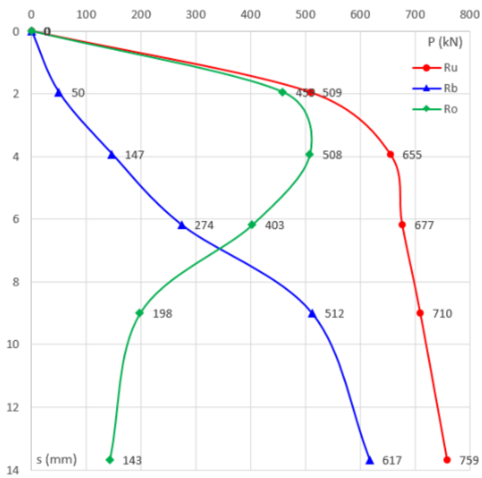

Figure 5. Diagrams of mobilized static force in component and cumulative forms obtained by in–situ DLT and by calculation

The pile DLT results show that for the first two impact of the drop weight, the load-bearing mechanism of the pile is realized predominantly by the shaft, while for the last two impacts, the load-bearing mechanism of the pile is realized predominantly by the base. The redistribution of the load between the shaft and the base of the pile with the increasing settlement is clearly observed. The ultimate value of the force mobilized by the pile shaft is realized by relatively small settlements of the order of 3mm. Reaching the ultimate force of the pile base requires significantly greater settlement than is the case with the shaft. With a further increase in the load and settlement of the pile, almost all the load capacity is realized by the base.

In the following stage of the test, an analysis of the pile bearing capacity with the redistribution of load between the shaft and the base was conducted. DLT was performed on the pile used in service, whereby when a higher kinetic energy is imparted, the tensile stresses are increased in concrete. In this sense, determining the pile behavior until reaching the ultimate strength, based on the DLT results, was accomplished using the known-accepted extrapolation methods for SLT. Since 5 DLTs were carried out, the test results, obtained by in–situ measurement and signal matching, are correlated by observing the entire test as a cyclic test (loading and unloading test in five cycles). Based on the test considered in this manner, the extrapolations were performed according to the Chin-Kondner and Decourt methods. Figure 6 sows the load-settlement curves obtained by extrapolation of pile DLT results according to the Chin-Kondner and Decourt methods and solutions of DLT. The load-settlement curve is practically an envelope for the solution obtained by DLT.

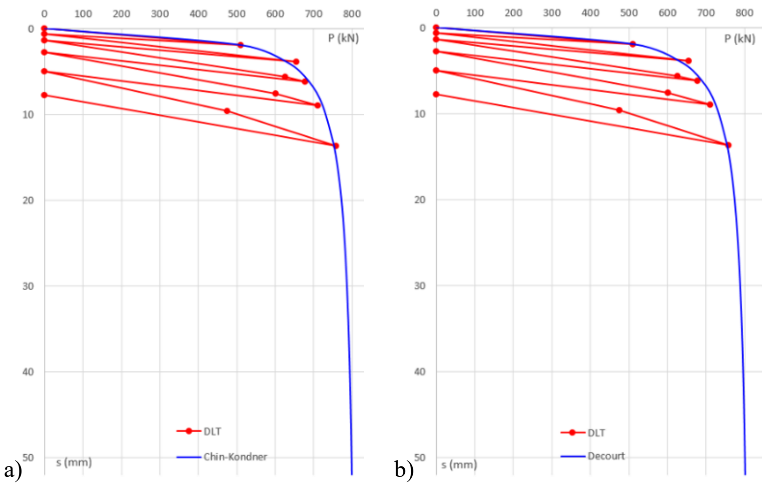

Figure 6. Solutions of DLT and of the load-settlement curve obtained by the extrapolation of pile DLT results according to the methods: a) Chin-Kondner, b) Decourt

The ultimate bearing capacity of the pile according to the Chin-Kondner method is R_u=817kN, while according to the Decourt method it is R_u=819kN. Considering that settlements for the ultimate strengths according to these two methods are higher than 52mm, determining the bearing capacity was conducted according to the criterion $D/10$ from the standard (EN 1997-1:2004, 2004). The ultimate bearing capacity of the pile according to the Chin-Kondner method, taking into account the criterion of ultimate settlement $D/10=520/10=52$mm from the standard (EN 1997-1:2004, 2004), is R_u=799kN, while according to the Decourt method it is R_u=801kN.

CONCLUSION

General models of distribution of bearing capacity of the base and the shaft are: the base bearing capacity is higher than the shaft bearing capacity and the shaft bearing capacity is higher than the base bearing capacity. However, the load redistribution between the shaft and the base of the pile is a factor that is not taken into account so much when designing structures founded in the ground. On the other hand, by examining the piles, this effect can be shown and it can indicate the possible consequences in terms of settlement and bearing capacity of the piles. It can be freely said that one of the most efficient, if not the most efficient method for the analysis of component loads, distribution, and even redistribution of loads between the shaft and the base, is the dynamic method, i.e. DLT. The geological environment in which the pile was constructed, the technology of making the pile and the geometry of the pile are factors that influence the load distribution from the pile to the soil.
In the presented example, the shaft bearing capacity is realized for the settlements lower than 1% of the pile diameter. After the ultimate bearing capacity of the shaft is realized, by further increasing the load, the share of the shaft in the total bearing capacity decreases to residual values. Then, the bearing capacity of the base increases until soil fracture in the soil occurs. In the presented example, with the aid of performed extrapolations, it was determined that the pile bearing capacity was 5.5% higher than the highest mobilized force obtained by DLT. After a considerable engagement of the base, depending on the type of soil in which the pile base is founded, the ultimate pile base bearing capacity values can be very rapidly reached.

Acknowledgment
This paper was financially supported by the Ministry of Education, Science and Technological Development of Republic of Serbia within the Project: 451-03-68/2020-14/200012. This support is gratefully acknowledged.

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