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PROCEDURE FOR CORRECTION OF BEARING CAPACITY OF PILES EXAMINED BY THE DYNAMIC LOAD TEST (DLT) ACCORDING TO THE STATIC LOAD TEST (SLT)

PROCEDURA ZA KOREKCIJU NOSIVOSTI ŠIPOVA ISPITANIH TESTOM DINAMIČKOG OPTEREĆENJA (DLT) PREMA TESTU STATIČKOG OPTEREĆENJA (SLT)

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Abstract

The paper shows the comparative analysis of behavior and bearing capacity of piles examined using the Dynamic Load Test (DLT) according to Static Load Test (SLT) results. The pile testing methodology is based on the existing ASTM standards and experiences of the authors of the paper. The pile tests were carried out using counterweights, reactive system, dynamic testing equipment, hardware and software for SLT and DLT. The data obtained by testing were statistically processed, and also a regression analysis of the linear function was conducted, resulting in the creation of the model for the change of mobilized static bearing capacity from DLT according to SLT. In addition, a procedure for correcting the solution of mobilized static bearing capacity from DLT according to SLT, is made by observing provisions of standard EN 1997-1:2004, so the average deviation of solutions from DLT according to SLT is reduced. Apart from that, through iterations, the value of correlation factor ξ_5 *is determined, taking into consideration solutions presented by SLT and DLT of piles of the real structures.*

Izvod

U radu je prikazana uporedna analiza ponašanja i nosivosti šipova ispitanih testom dinamičkog opterećenja (DLT - Dynamic Load Test) prema rezultatima testa statičkog opterećenja (SLT - Static Load Test). Metodologija ispitivanja šipova zasniva se na postojećim ASTM standardima i iskustvima autora rada. Ispitivanja šipova sprovedena su primenom kontratereta, reaktivnog sistema, opreme za dinamičko ispitivanje, hardverima i softverima za SLT i DLT. Statistički su obrađeni podaci dobijeni ispitivanjima, a takođe je sprovedena i regresiona analiza za linearnu funkciju, tako da je dobijen model promene mobilisane statičke nosivosti iz DLT prema SLT. Dodatno je razvijena procedura za korekciju rešenja mobilisane statičke nosivosti iz DLT prema SLT uvažavajući odredbe standarda EN 1997-1:2004, tako da se umanjuje prosečno odstupanje rešenja iz DLT prema SLT. Pored toga, kroz iteracije, određena je vrednost faktora korelacije ξ_5*, uzimajući u obzir rešenja prikazana SLT i DLT ispitivanjem na šipovima realnih objekata.*

INTRODUCTION

Testing of piles dates back to the period when engineering-technological-structural approaches started to be used in the analysis of piles of large structures. Over time, different pile testing techniques were developed, while the development of electronic instruments, hardware components, and software engineering facilitated digitalization and monitoring of pile behavior in real time with post-processing of data. In general, pile bearing capacity tests can be classified as:
- Static Load Test (SLT),
- Dynamic Load Test (DLT),
- Statnamic Load Test (SNLT),
- Bi-Directional Static Load Test (BDSLT).

Most frequently applied tests in practice are SLT and DLT. In a large number of cases, geological conditions of the location on which a structure is being built, can be considerably nonuniform in terms of physical-mechanical characteristics of the soil and stratification layers of depth. All this increases the level of unreliability in the analysis of behavior and bearing capacity of piles. Solving such complex problems most often boils down to increasing the number of testing piles. The effect of the test is additionally increased if more tests are performed on test piles than on service piles, since in this way the piles can be loaded to their ultimate capacity.

After performing DLT of the pile, it is necessary to determine its mobilized bearing capacity, however, it is also necessary to analyze to what extent the obtained solution represents actual (real) bearing capacity which is obtained by performing SLT. Regarding that the research presented in this paper, specifically, considers the issue of comparison and correction of bearing capacity obtained from DLT, according to performed SLT of the piles, this facilitates the research as the literature in this specific field is relatively readily available. The issue of comparative analysis of the results of SLT and DLT of piles was presented in different approaches in the following papers /3, 6, 9, 11, 12, 13, 16, 17/, where comparative solutions for discrete values of the bearing capacity of piles are provided. In certain papers, there is an additional presentation of solutions obtained via test load curves (load-settlement) for SLT and DLT. The research concerning the comparative analysis of bearing capacity of piles from DLT using different methods: CAP-WAP, TNOWAVE and SIMBAT, and the comparison with results from SLT are presented in /14/. The analysis of the sensitivity of DLT parameters that participate in the analysis of the pile bearing capacity, comparing the solutions to SLT, is presented in /15/.

In relation to previously mentioned papers, this research presents the statistical analysis of the deviation of bearing capacity from DLT according to SLT, and a procedure that corrects the test results of DLT according to SLT is additionally developed, observing the provisions of the standard EN 1997-1:2004, /5/.

METHODOLOGY OF SLT AND DLT OF PILES

SLT of piles belongs to the group of high strain tests (HST) and it is the most reliable and most relevant test in the analysis of behavior of piles and for determining their bearing capacity. This test proves the design force through the mobilized static bearing capacity, but also the ultimate capacity of the pile. If SLT is performed on the service pile, then the design force is being proven, and if SLT is performed on a test pile, then the ultimate capacity is being proven. There are two variants of the technical solution that can be employed to perform this test: the counterweight test and the reactive pile test. In both variants, what is measured is the pile head settlement, depending on the load increments applied on the pile head. All SLTs of piles, whose results are presented in this paper, are conducted using the following equipment: hydraulic presses of various capacities, hydraulic system (pumps), motor-power generator, steel calottes, plates, spacers, reference system, analogue and digital comparators, software for processing and visualization of data and the surveying system (leveling and bar code staves) for pile deformation monitoring /4/. With this equipment it is possible to conduct testing, analyze pile behavior, determine bearing capacity of the pile and collect data in real time and/or discrete time intervals. Comparators readout and/or store data about the pile settlement, while surveying instruments perform the control of pile settlement and correction of settlement of reference beams. Pile tests, according to SLT, are conducted in compliance with the standard ASTM D1143, /1/. After the conducted SLT, a test load curve is constructed. Since tests presented in this paper, in a large number of cases were conducted on service piles, no extrapolations of test load curves are presented. These extrapolations are neither the subject of research in this paper.

DLT also belongs to the group of HST and is performed with a weight and crane trucks, or by specially designed equipment for dynamic testing. Considering that there are several variants of equipment and methods of performing DLT of piles, this paper shows the tests performed using the independent system for lifting of modular weight. DLT, in a number of cases, determines the mobilized static bearing capacity of the pile which proves the design force. All DLTs of piles, whose results are presented here, are carried out using the following equipment: modular steel supporting structure fitted and connected to the pile head, modular drop weights, hydraulic system for lifting of drop weights to a specific height, drop weight arresting system (braking system), motor with a power generator, wooden blocks (dampeners), sensors (integrated accelerometers and strain gauges), hardware system for conversion and acquisition of data, software system for PDA-DLT /7/ and DLT-WAVE /8/ processing and visualization of data and a surveying system (leveling and bar code staves) for deformation monitoring. PDA-DLT software is used for in-situ DLT monitoring and data processing; DLT-WAVE software is used for signal matching of the nonlinear numerical pile-soil interaction model and for the signal obtained from in-situ DLT of the pile. With this equipment, it is possible to conduct testing of bearing capacity of piles and collect data in real time, as well as perform the post-processing of data. Bearing capacity tests of piles, according to DLT, were conducted in compliance to ASTM D4945, /2/. The mathematical formulation of the problem of DLT is based on following theories: rigid-body dynamics, wave theory, method of characteristics, nonlinear theory, dynamics of structures, soil-structure interaction (SSI) theory, and signal processing, /4/. On the occasion of the dynamic loading of the pile applied to the pile head, due to the free fall of the drop weight of appropriate mass *m* and from appropriate height *h*, the impact energy is transmitted and there occurs the pile deformation (settlement). By using the fundamental principles of mechanics, via energy conservation law, one may formulate the DLT problem by establishing the relationship of potential energy equivalence E_p (drop weight elevated to height *h*), and kinetic energy E_k (drop weight freely dropped on the pile head). The sensors, fitted on pile head extension, or the pile head itself, register strains and accelerations of the pile over time. Based on the measured strains $\varepsilon(t)$, modulus of elasticity of concrete *E*, and area of the pile cross-section *A*, the force $F(t)$ is calculated according to, /10/:

$$F(t)=\varepsilon(t)EA\,. \tag{1}$$

On the other hand, based on the measured accelerations, employing the first numerical integration produces velocity $v(t)$ and calculates force $F(t)$ according to:

$$F(t)=v(t)Z=v(t)\frac{EA}{c}\,, \tag{2}$$

where: *Z* is pile impedance (depending on the material characteristics and pile cross-section geometry); *c* is the wave propagation velocity in concrete. Diagrams of the forces obtained by measuring strains and accelerations in time represent a basis for interpretation of DLT results. The total value of the 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 $F\uparrow$:

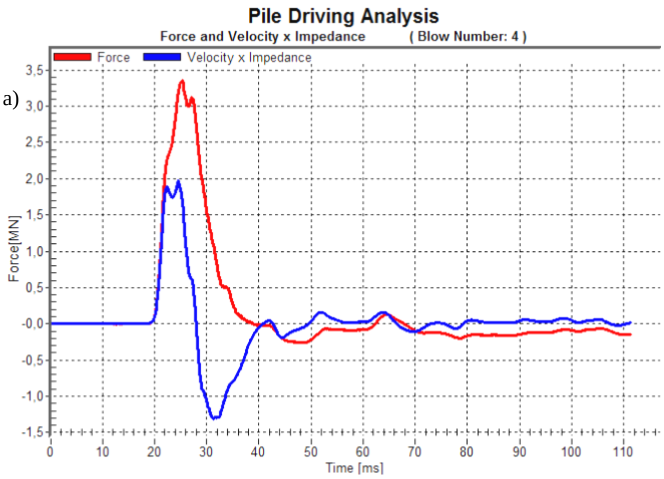
$$R_{tot}=F^{\downarrow}(t_{\max})+F^{\uparrow}\left(t_{\max}+2\frac{L}{c}\right), \tag{3}$$

where: *L* is the length of pile; while in the general case the forces obtained from the wave are calculated according to:

$$F(t)^{\downarrow}=0.5(F(t)+Zv(t)^{\downarrow})\,,$$
$$F(t)^{\uparrow}=0.5(F(t)-Zv(t)^{\uparrow})\,. \tag{4}$$

Bearing capacity of piles is determined from the in-situ DLT results, by using the indirect method. In an indirect way, pile bearing capacity is determined using the signal matching procedure, which is an iterative procedure of finding the static and dynamic soil parameters with the goal to obtain a calculation signal which is the best match with the measured signal. More accurately, the signal of the nonlinear numerical model of pile-soil interaction is matched to the measured signal from an in-situ DLT. The numerical pile model in interaction with the soil is a continual mathematical model with continually distributed masses and modeled stiffness. Measured signal comprises an upward traveling wave, i.e., the wave traveling from the base to the head of the pile, because in essence it contains data on the soil resistance. Figure 1a shows examples of the diagram of force variation over time obtained by in-situ DLT measured strains and accelerations, while Fig. 1b shows the conducted signal matching of the upward traveling wave of the nonlinear numerical pile-soil interaction model with the signal obtained by in-situ DLT of piles in the field.

Almost all SLTs, shown in this paper, were conducted with the aim of testing the behavior of service piles at a force level slightly higher than the design force, and not to their ultimate capacity. In this sense, all DLTs were conducted with the aim of testing the behavior of service piles at a force level slightly higher than the design force. Figure 2 shows the general test load curve model of the service pile from SLT, design force $F_{c,d}$ and mobilized static bearing capacity $R_{c,m,DLT}$ obtained from DLT of the pile.

a)


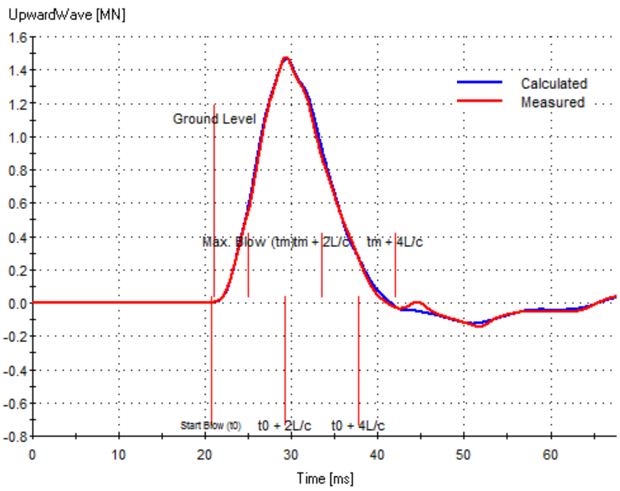
b)


Figure 1. a) Force vs. time obtained by in-situ DLT measurement; b) signal matching of upward traveling wave.

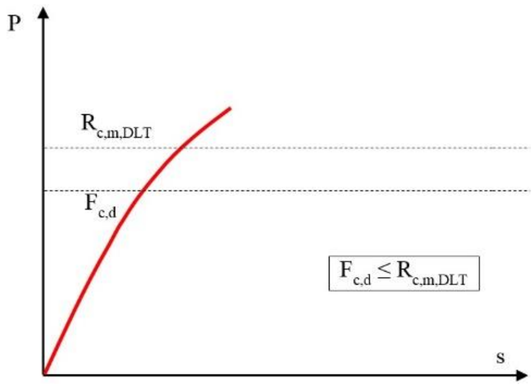


Figure 2. General test load curve model of service pile from SLT, design force $F_{c,d}$ and mobilized static bearing capacity $R_{c,m,DLT}$ obtained from DLT of the pile.

CHARACTERISTICS OF CONDUCTED SLT AND DLT

SLT and DLTs are conducted on seven different models of piles built on seven different locations. Locations differ in terms of geology and are situated several tens or even hundreds of km apart, and the following structures are built on them: office building; bridges connecting roads; bank revetment; wind turbines; industrial hall; and industrial complex. Therefore, the test examples are purposefully selected for their diversity in terms of geology in which piles are constructed, pile building technology and types of buildings.

Table 1. Parameters of tested piles, SLT and DLT equipment.

pile no.	pile type	D (cm)	L (m)	MB	SLT		DLT	
					action	G_{SLT} (t)	action	G_{DLT} (t)
1	CFA	60	10	30	counterweight	82.5	modular weight	2.5
2	Franki	52	15.4	30	counterweight	198	modular weight	2.5
3	bored	80	24	35	reactive piles	>220	modular weight	5
4	bored	100	23.5	50	reactive piles	>850	modular weight	15
5	bored	120	27	30	reactive piles	>737	modular weight	10
6	CFA	60	20	40	counterweight	484	modular weight	5
7	driven	40.6	12.5	30 (+pipe)	reactive piles	>110	modular weight	2.5

Table 1 presents parameters of tested piles, SLT and DLT equipment: D is pile diameter; L pile length; MB concrete class; G_{SLT} weight/reaction in SLT, G_{DLT} drop weight mass in DLT. Piles are built using boring, CFA (continuous flight auger) and pile driving technologies. Counterweight is used for certain piles for SLT, because it is disassembled after the performed tests and used for testing piles at other locations.

In some cases, reactive systems made up of steel members are used which are also disassembled after completed tests and used for further tests. In situations when it is not possible to provide sufficient bearing capacity, either with a counterweight or with a reactive system of steel members, reactive systems of reinforced concrete supports are implemented. They have a single-use function - only one SLT of piles is performed on them, after which they are demolished.

Figures 3a-9a show formed counterweights and reactive systems with presses and equipment set for SLT of piles, while Figs. 3b-9b show equipment set for DLT of the piles. Figures 3c-9c show diagrams of the variation of force over time, obtained by in-situ DLT measurement of strains and accelerations.

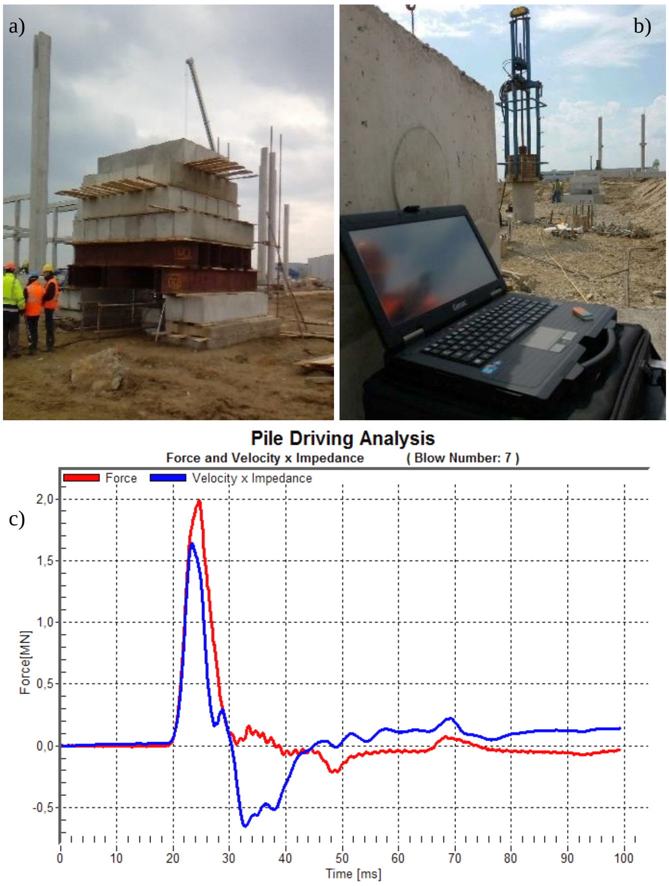


Figure 3. Pile no.1: a) SLT of pile; b) DLT of pile; c) force signals obtained by DLT.

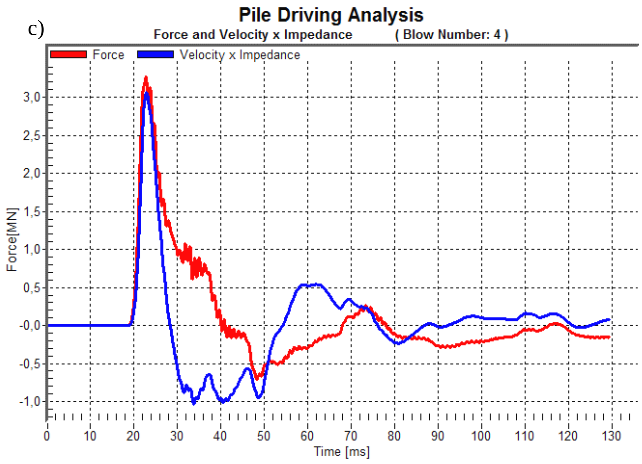


Figure 4. Pile no.2: a) SLT of pile; b) DLT of pile; c) force signals obtained by DLT.

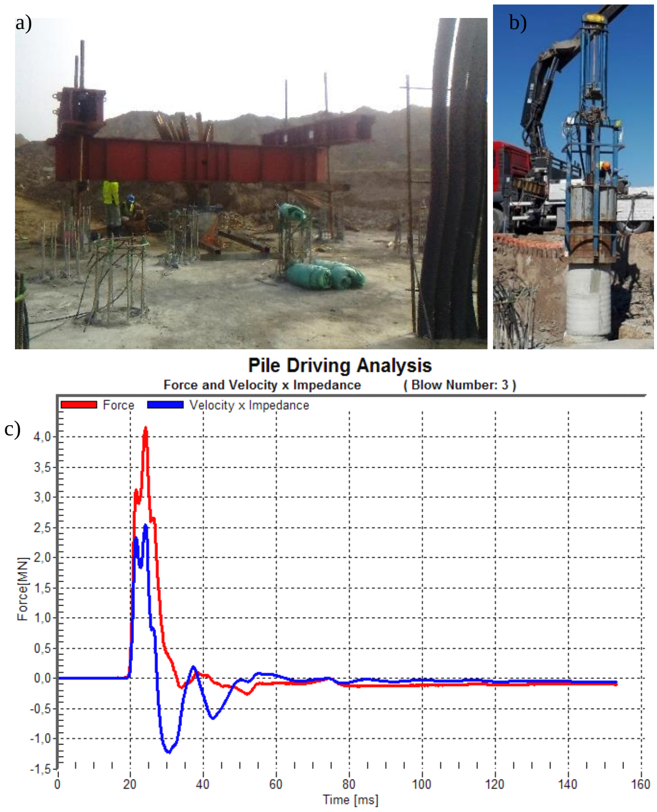


Figure 5. Pile no.3: a) SLT of pile; b) DLT of pile; c) force signals obtained by DLT.

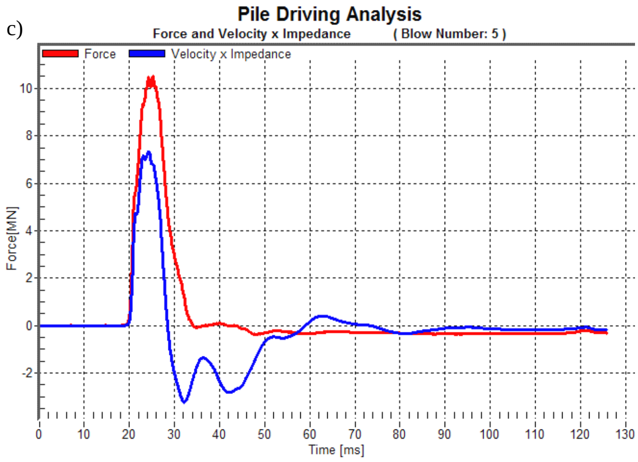


Figure 6. Pile no.4: a) SLT of pile; b) DLT of pile; c) force signals obtained by DLT.

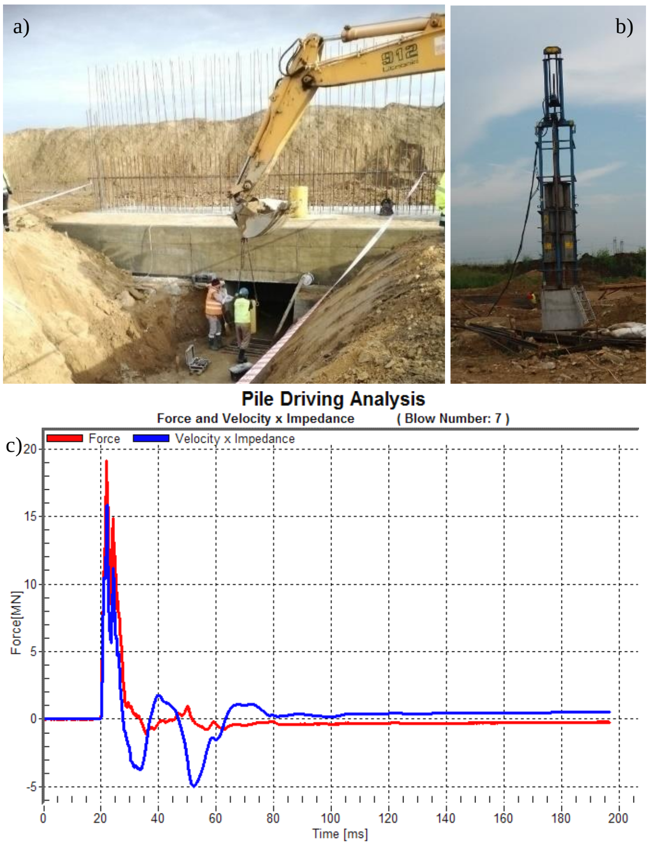


Figure 7. Pile no.5: a) SLT of pile; b) DLT of pile; c) force signals obtained by DLT.

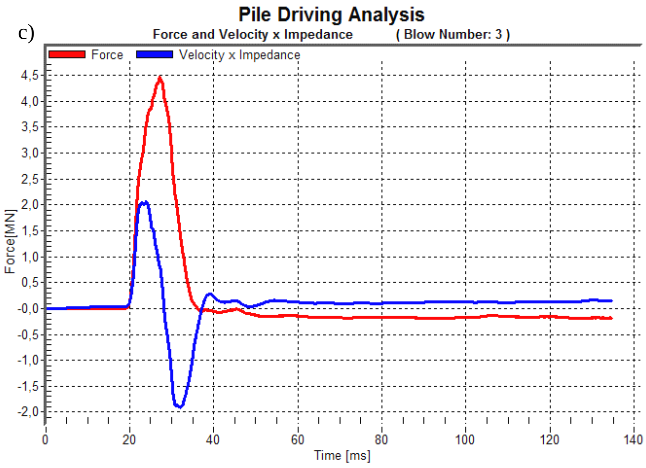


Figure 8. Pile no.6: a) SLT of pile; b) DLT of pile; c) force signals obtained by DLT.

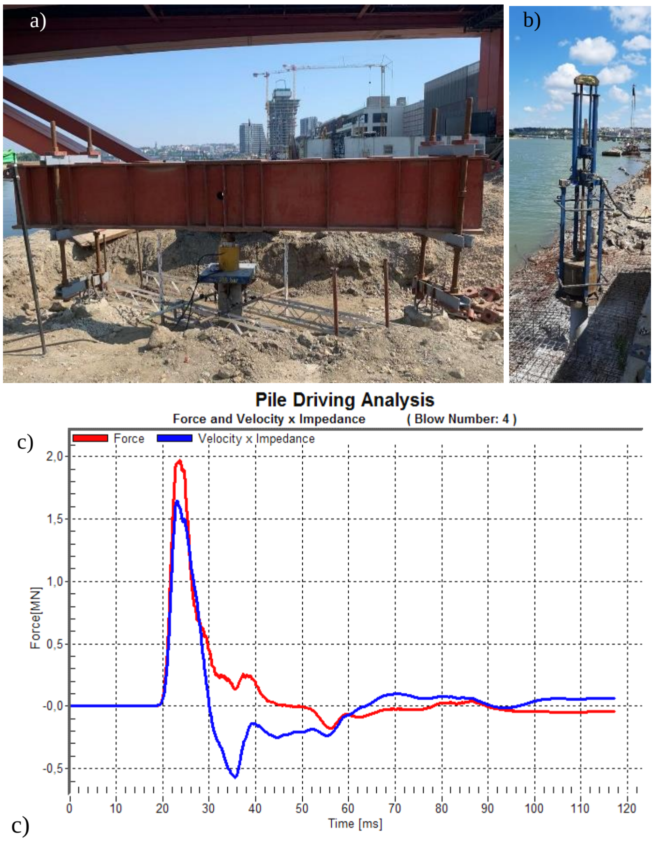


Figure 9. Pile no.7: a) SLT of pile; b) DLT of pile; c) force signals obtained by DLT.

COMPARATIVE ANALYSIS OF BEARING CAPACITY OF DLT OF PILES ACCORDING TO SLT

The comparison of DLT results with SLT was conducted taking into consideration the s_{DLT} settlement equivalence obtained from DLT bearing capacity and s_{SLT} settlement obtained from SLT:

$$s_{DLT} = s_{SLT} \,. \tag{5}$$

Based on the condition set in this way, interpolations of test load curves from SLT are conducted, and corresponding forces $P_{int,SLT}$ were obtained. In the first step, the analysis of the percentage deviation Δ of the DLT solution from the SLT solution for individual piles is conducted, while in the second step, a deviation that takes into consideration all the piles is shown. Table 2 presents results of SLT and DLT for seven considered piles.

Table 2. Results of SLT and DLT of piles and percentage deviation of results SLT/DLT by the tests.

pile no.	SLT			DLT				Δ (%)
	P_{max} (kN)	s_{max} (mm)	$P_{int,SLT}$ (kN)	R_{tot} (kN)	E_k (kNm)	$R_{c,m,DLT}$ (kN)	s_{DLT} (mm)	
1	750	1.3	711	1732	3.8	768	1.2	7.96
2	1800	7.3	1570	3726	15.2	1645	5.8	4.79
3	2200	2.7	1653	3251	7.9	1726	2	4.44
4	8500	11.7	6180	7890	47	6748	6.8	8.85
5	6800	42.5	3415	17110	58.9	3781	4.5	9.58
6	4400	6.6	4110	5685	14.1	4490	5.7	8.97
7	1110	28.7	670	2045	11.4	718	6.3	6.42

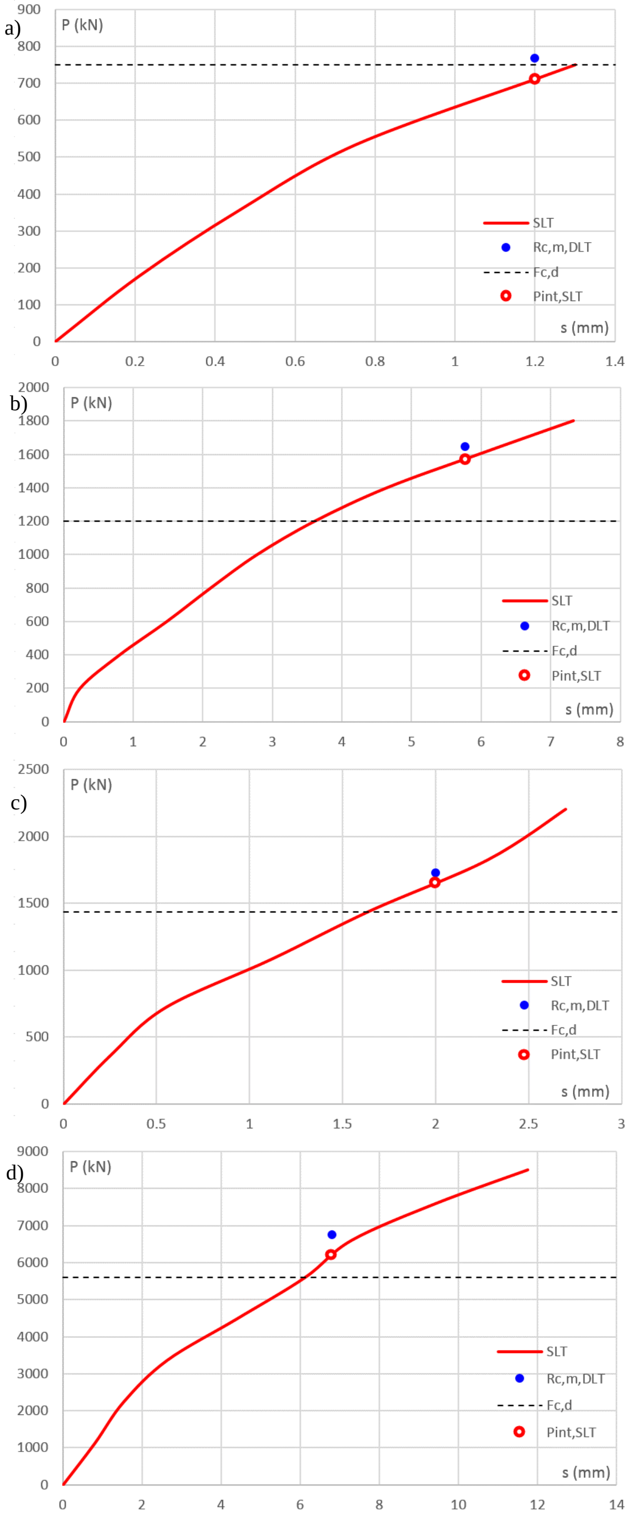
Markings in Table 2 are: P_{max} - maximal force used in SLT on piles; s_{max} - corresponding maximal settlement obtained for P_{max} from SLT; $R_{c,m,DLT}$ - mobilized static bearing capacity obtained from DLT of piles; s_{DLT} - corresponding settlement obtained for $R_{c,m,DLT}$ from DLT. R_{tot} and E_k were previously defined.

Mobilized static load capacities obtained from DLT of piles, as already stated, are determined using the iterative procedure of signal matching using DLT-WAVE software. Due to the complexity and extensiveness of the calculation and a large number of diagrams (signals) it is not possible to present all the phases of signal matching calculation in this paper. In this sense, in addition to the presented key diagrams in Figs. 3c-9c, the final values of mobilized static bearing capacities are listed in Table 2. The highest deviation of the results is obtained for pile number 5.

The average deviation of bearing capacity from DLT, according to SLT is up to Δ_m = 7.29 %. It should be mentioned that SLT and DLT were not conducted on the same piles except in the case of the pile number 4. Also, it should be mentioned that certain piles were slightly more spaced from one another, which may additionally affect the results, considering the spatial variation in geology. A more detailed analysis of the pile spacing is:

- pile no. 1: foundation footings with piles of the industrial hall - DLT and SLT were several hall spans apart;
- pile no. 2: foundation raft and piles of the wind turbine - DLT and SLT were performed on one foundation at a distance of a couple of meters, because the diameter of the wind turbine raft is around 15 m;
- pile no. 3: foundation raft and piles of the wind turbine - DLT and SLT were performed on one foundation at a distance of a couple of meters, because the diameter of the wind turbine raft is around 20 m;
- pile no. 4: foundation raft and piles of the office building - DLT and SLT performed on the same pile (firstly DLT, and afterwards SLT);
- pile no. 5: foundation raft and piles of the road bridge - DLT and SLT were performed at a certain distance but on the same column footing;
- pile no. 6: foundation raft and piles of the industrial complex - DLT and SLT were performed within the common foundation raft which is one part of the industrial complex;
- pile no. 7: bank revetment piles - DLT and SLT were performed at a certain distance from each other (several tens of meters), considering that the piles were set in a linear fashion along the bank revetment.

Figure 10 shows test load curves of SLT of piles, having the mobilized static bearing capacity $R_{c,m,DLT}$ obtained from DLT of piles, the design force $F_{c,d}$ and interpolate force $P_{int,SLT}$ from test load curves from SLT for $R_{c,m,DLT}$ from DLT where $s_{DLT} = s_{SLT}$. After analyzing all diagrams, it can be stated that by using DLT, slightly higher values are obtained in comparison to the SLT results, if the comparison is conducted using the settlement equivalence $s_{DLT} = s_{SLT}$.



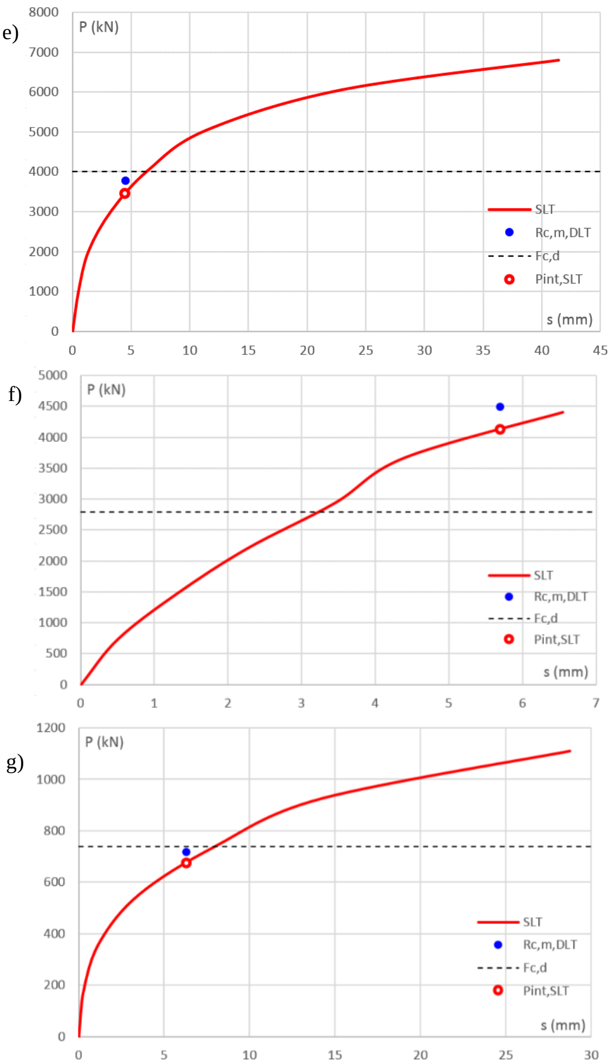


Figure 10. Test load curves of SLT of piles, having mobilized static bearing capacity $R_{c,m,DLT}$ obtained from DLT of piles, design force $F_{c,d}$ and an interpolated force $P_{int,SLT}$ from test load curves from SLT for $R_{c,m,DLT}$ from DLT where $s_{DLT} = s_{SLT}$: a) pile no.1; b) pile no.2; c) pile no.3; d) pile no.4; e) pile no.5; f) pile no.6; g) pile no.7.

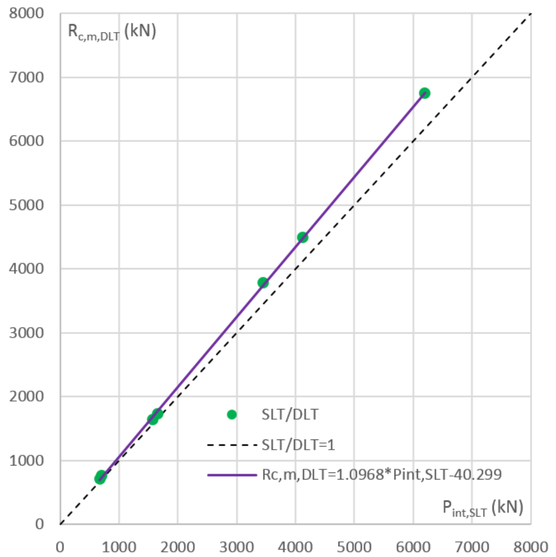


Figure 11. Compared bearing capacity $R_{c,m,DLT}$ from DLT and interpolated force $P_{int,SLT}$ from SLT for the same settlement level $s_{DLT} = s_{SLT}$.

The comparison of bearing capacity $R_{c,m,DLT}$ from DLT and interpolated force $P_{int,SLT}$ from SLT, for the same level of settlement $s_{DLT} = s_{SLT}$, is presented in Fig. 11. Regression analysis is conducted for linear function $R_{c,m,DLT} = 1.0968 \cdot P_{int,SLT} - 40.299$ and the determination coefficient $r^2 = 0.999$. Also, an ideal situation SLT/DLT = 1 is presented, when the values of SLT and DLT results are identical. It is evident that for higher values of bearing capacity from DLT, slightly higher deviation is obtained in comparison to the solution of SLT of the piles.

DEVELOPMENT OF PROCEDURE FOR CORRECTION OF BEARING CAPACITY OBTAINED FROM DLT ACCORDING TO SLT RESULTS

Considering previously presented results of conducted SLT and DLT of piles and the fact that by implementing DLT slightly higher values of bearing capacity in comparison to SLT results are obtained, a procedure for correction of bearing capacity obtained from DLT is developed. The procedure is based on the calculation of bearing capacity from the conducted SLT and DLT according to EN 1997-1:2004, /5/. However, the calculation of bearing capacity according to SLT and DLT is not analyzed, rather the relations DLT-SLT are analyzed via corresponding factors from EN 1997-1:2004, /5/.

Figure 12 shows the general case of the test load curve (load-settlement) obtained after a performed SLT of a pile. The figure shows bearing capacity values $R_{c,m,SLT}$, $R_{c,k,SLT}$ and $R_{c,d,SLT}$. The value of $R_{c,m,SLT}$ was determined from the settlement conditions $D/10$. The value of $R_{c,k,SLT}$, in relation to $R_{c,m,SLT}$, is the function of correlation factors ξ_1 and ξ_2, while the value $R_{c,d,SLT}$, in relation to $R_{c,k,SLT}$, is the function of partial factor for total resistance γ_t.

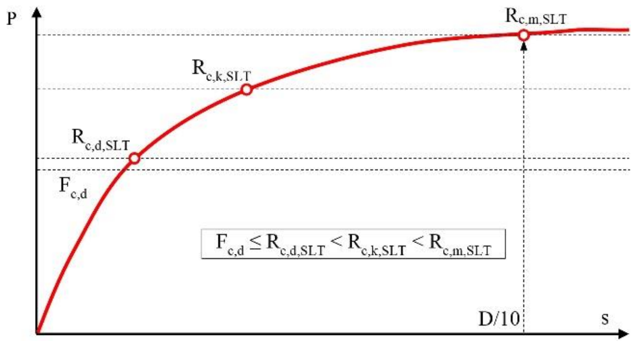


Figure 12. General case of the test load curve (load-settlement) obtained after one performed SLT of the pile.

Figure 13 shows the general case of the obtained discrete values of DLT, based on multiple weight drops on the pile head, whereby the weight drop height was incrementally increased. Based on discrete values (force-settlement) obtained in this way, a regression analysis of the corresponding function is conducted, which provides the best fitting of results of DLT and constructs the regression curve. The construction of the regression curve, from DLT, is used to compare the results from DLT according to SLT from 0 to $D/10$ pile settlement values. Also, here are presented values of $R_{c,m,DLT}$, $R_{c,k,DLT}$, and $R_{c,d,DLT}$. The value of $R_{c,m,DLT}$ is determined from settlement condition $D/10$, the same as in the solution for

SLT. The value $R_{c,k,DLT}$ in relation to $R_{c,m,DLT}$ is the function of correlation factors ξ_5 and ξ_6, while value of $R_{c,d,DLT}$, in relation to $R_{c,k,DLT}$ is the function of partial factor for total resistance γ_t. Figure 14 shows the test load curve from SLT, regression curve from DLT and $R_{c,m,DLT}$, $R_{c,m,SLT}$, $R_{c,k,DLT}$, $R_{c,k,SLT}$, $R_{c,d,DLT}$, and $R_{c,d,SLT}$. Bearing capacity $R_{c,m,DLT}$ from DLT and bearing capacity $R_{c,m,SLT}$ from SLT are obtained for the same level of settlement $s_{DLT,D/10} = s_{SLT,D/10}$, whereby, in the general case, $R_{c,m,DLT} > R_{c,m,SLT}$.

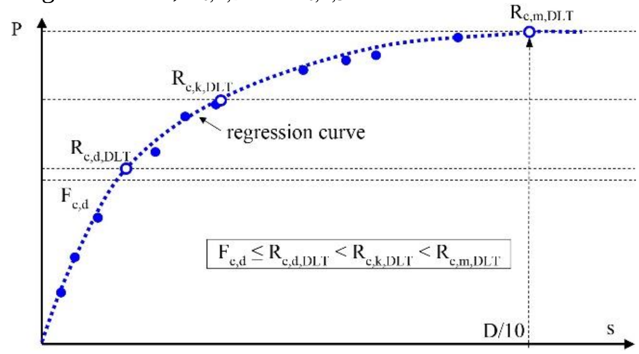


Figure 13. General case of obtained discrete values of DLT based on multiple weight drops on pile head, whereby drop height is incrementally increased.

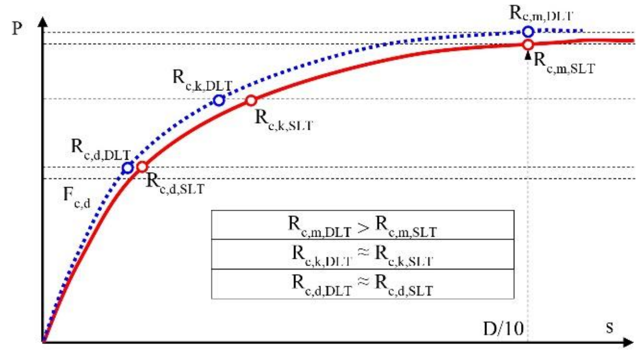


Figure 14. Test load curve from SLT and regression curve from DLT; $R_{c,m,DLT}$, $R_{c,m,SLT}$, $R_{c,k,DLT}$, $R_{c,k,SLT}$, $R_{c,d,DLT}$, and $R_{c,d,SLT}$ bearing capacities.

This fact was indicated in the previous section, accordingly, there arises the need to correct the solution from DLT according to the solution from SLT. Considering that according to EN 1997-1:2004 /5/, for one SLT and one DLT of the pile, the correlation factors ξ_5 and ξ_6 for DLT are higher than correlation factors ξ_1 and ξ_2 for SLT, thus the reliability of the solution provided by SLT is higher than that of DLT. In that sense, according to EN 1997-1:2004 /5/, it can be conditionally stated that bearing capacity of $R_{c,k,DLT}$ is equal or approximately equal to bearing capacity $R_{c,k,SLT}$, considering that for $R_{c,m,DLT}$ and $R_{c,m,SLT}$ different values of correlation factor are used so that identical or approximately identical solutions for $R_{c,k,DLT}$ and $R_{c,k,SLT}$ would be obtained. In this case, as it is said, it can be conditionally stated that bearing capacities $R_{c,k,DLT} = R_{c,k,SLT}$ (equal), or $R_{c,k,DLT} \approx R_{c,k,SLT}$ (approximately equal), but certain displacements are different for these bearing capacities as can be seen in Fig. 14. On the other hand, bearing capacities $R_{c,d,DLT}$ and $R_{c,d,SLT}$ are only reduced with the partial factor for total resistance γ_t, so it holds for them that $R_{c,d,DLT} = R_{c,d,SLT}$ or $R_{c,d,DLT} \approx R_{c,d,SLT}$. Corresponding displacements for these bearing capacities are different, as can be seen in Fig. 14.

Figure 15 shows the test load curve from SLT and the regression curve from DLT. Also, a presentation of the general case of mobilized force P_{DLT} obtained from DLT of the pile is provided in the interval ($R_{c,d,DLT}$, $R_{c,m,DLT}$), and the corresponding value of the force in the pile P_{SLT} from SLT for the same level of settlement $s_{DLT} = s_{SLT}$ from DLT and SLT. The correction of the solution is conducted by considering the value interval from $R_{c,d,DLT}$ or $R_{c,d,SLT}$ to the bearing capacity $R_{c,m,DLT}$, i.e., $R_{c,m,SLT}$.

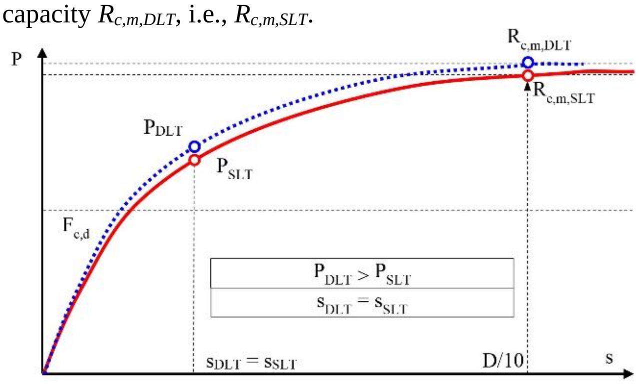


Figure 15. Test load curve from SLT and regression curve from DLT; general case of mobilized force P_{DLT} obtained from DLT of the pile and corresponding value of force P_{SLT} in the pile from SLT for the same level of settlement $s_{DLT} = s_{SLT}$ from DLT and SLT.

The correction procedure is developed based on the (conditional) equivalence of solutions obtained by SLT and DLT. The design value of bearing capacity of the pile $R_{c,d,SLT}$, tested by SLT, can be presented by the expression:

$$R_{c,d,SLT} = \frac{\min\left\{\dfrac{(R_{c,m,SLT})_{mean}}{\xi_1};\dfrac{(R_{c,m,SLT})_{min}}{\xi_2}\right\}}{\gamma_t}, \quad (6)$$

while the design value of bearing capacity of the pile $R_{c,d,DLT}$, tested by DLT, can be presented by the expression:

$$R_{c,d,DLT} = \frac{\min\left\{\dfrac{(R_{c,m,DLT})_{mean}}{\xi_5};\dfrac{(R_{c,m,DLT})_{min}}{\xi_6}\right\}}{\gamma_t}. \quad (7)$$

Equivalence of the design values of the pile $R_{c,d,SLT} = R_{c,d,DLT}$, according to SLT and DLT, results in:

$$\frac{\min\left\{\dfrac{(R_{c,m,SLT})_{mean}}{\xi_1};\dfrac{(R_{c,m,SLT})_{min}}{\xi_2}\right\}}{\gamma_t} = \frac{\min\left\{\dfrac{(R_{c,m,DLT})_{mean}}{\xi_5};\dfrac{(R_{c,m,DLT})_{min}}{\xi_6}\right\}}{\gamma_t}, \quad (8)$$

i.e.:

$$\min\left\{\frac{(R_{c,m,SLT})_{mean}}{\xi_1};\frac{(R_{c,m,SLT})_{min}}{\xi_2}\right\} = \min\left\{\frac{(R_{c,m,DLT})_{mean}}{\xi_5};\frac{(R_{c,m,DLT})_{min}}{\xi_6}\right\}. \quad (9)$$

Considering that the value of partial factor for total resistance γ_t is identical, both in SLT and in DLT, further considerations are not done for this factor, but rather for the correlation factors ξ_1 and ξ_2 in SLT, and correlation factors

ξ_5 and ξ_6 in DLT, because these factors differ. If the previous expression is separated by *mean* and *min* values, the following expression is obtained:

$$\frac{(R_{c,m,SLT})_{mean}}{\xi_1}=\frac{(R_{c,m,DLT})_{mean}}{\xi_5}\,,$$

$$\frac{(R_{c,m,SLT})_{min}}{\xi_2}=\frac{(R_{c,m,DLT})_{min}}{\xi_6}\,, \qquad (10)$$

i.e.: $$\frac{(R_{c,m,SLT})_{mean}}{(R_{c,m,DLT})_{mean}}=\frac{\xi_1}{\xi_5}\,,\quad \frac{(R_{c,m,SLT})_{min}}{(R_{c,m,DLT})_{min}}=\frac{\xi_2}{\xi_6}\,. \qquad (11)$$

The preceding expression can be written by introducing new correction coefficients of DLT results in relation to SLT results, whose designations are c_{mean} and c_{min}:

$$c_{mean}=\frac{\xi_1}{\xi_5}\,,\quad c_{min}=\frac{\xi_2}{\xi_6}\,. \qquad (12)$$

The corrected mobilized static bearing capacity of the pile $R_{c,m,DLT/SLT}$ is determined by multiplication of $R_{c,m,DLT}$ from DLT with correction coefficients c_{mean} and c_{min}:

$$(R_{c,m,DLT/SLT})_{mean}=c_{mean}(R_{c,m,DLT})_{mean}\,, \qquad (13)$$

$$(R_{c,m,DLT/SLT})_{min}=c_{min}(R_{c,m,DLT})_{min}\,. \qquad (14)$$

The final solution is obtained by minimization of $(R_{c,m,DLT/SLT})_{mean}$ and $(R_{c,m,DLT/SLT})_{min}$:

$$\min\left\{(R_{c,m,DLT/SLT})_{mean};(R_{c,m,DLT/SLT})_{min}\right\}. \qquad (15)$$

In cases when the correction is conducted for one single pile, as the subject of one DLT and one SLT, the correction coefficients c_{mean} and c_{min}, in compliance with the standard EN 1997-1:2004, /5/, become:

$$c_{mean}=\frac{\xi_1}{\xi_5}=\frac{1.4}{1.633}=0.857\,,\quad c_{min}=\frac{\xi_2}{\xi_6}=\frac{1.4}{1.55}=0.903\,. \qquad (16)$$

Correlation factors ξ_5 and ξ_6 of DLT, for the tests of one pile, are determined by extrapolation of correlation factor value for multiple piles according to EN 1997-1:2004, /5/. According to EN 1997-1:2004 /5/, correlation factors ξ_5 and ξ_6 in the analysis of the bearing capacity of piles by DLT are defined for a minimum of two and more piles, however, in practice there is often a situation when only one pile needs to be tested by DLT. Considering that for the interval of values from $R_{c,d,SLT}$ or $R_{c,d,DLT}$ to $R_{c,m,SLT}$, i.e., $R_{c,m,DLT}$, the correction of the solution from DLT according to the solution from SLT is conducted using correlation factors ξ_1 and ξ_5 (in case of SLT and DLT of a single pile), because they are relevant for it, it can be concluded that all the values of mobilized static forces P_{DLT} from DLT can be sufficiently reliably corrected according to these correlation factors, i.e., according to the expression:

$$P_{DLT/SLT}=\frac{\xi_1}{\xi_5}P_{DLT}\,,\ \text{i.e.,}\ \ P_{DLT/SLT}=c_{mean}P_{DLT}\,, \qquad (17)$$

$$P_{DLT/SLT}=\frac{\xi_2}{\xi_6}P_{DLT}\,,\ \text{i.e.,}\ \ P_{DLT/SLT}=c_{min}P_{DLT}\,. \qquad (18)$$

Considering that correction coefficients c_{mean} and c_{min} are smaller than 1, this automatically means that the values of mobilized static forces P_{DLT} from DLT and mobilized static bearing capacity $R_{c,m,DLT}$ from DLT are reduced for the purpose of correction and approximation of the solution in accordance with SLT. In the preceding section, it has been stated, that for the same level settlement s_{DLT} of the calculated DLT and settlement s_{SLT} of the measured SLT, a higher mobilized static force PDLT of the calculated DLT is obtained, in comparison to the interpolated static force P_{SLT} obtained by SLT:

$$s_{SLT}=s_{DLT}\,;\ \ P_{DLT}>P_{SLT}\,. \qquad (19)$$

Figure 16 shows the principle of general comparative analysis of test results of DLT according to SLT. More accurately, what is obtained are the discrete value of mobilized static force P_{DLT} obtained from DLT, in the interval ($R_{c,d,DLT}$, $R_{c,m,DLT}$), corrected mobilized static force $P_{DLT/SLT}$ obtained from DLT and the test load curve.

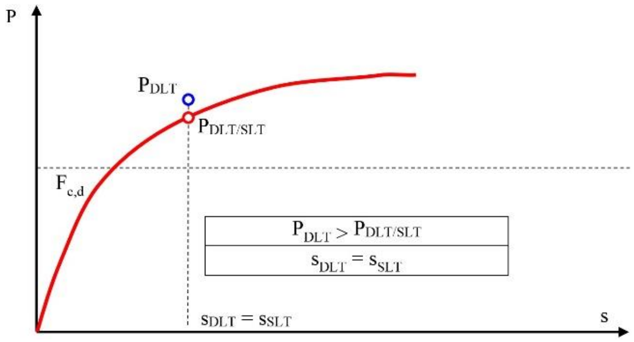


Figure 16. Principle of comparative analysis of the test result of DLT according to SLT - schematic presentation of relations of discrete values of mobilized static force P_{DLT} obtained from DLT in the interval ($R_{c,d,DLT}$, $R_{c,m,DLT}$), corrected mobilized static force $P_{DLT/SLT}$ obtained from DLT and test load curve.

By processing data obtained by tests and presented research results in the previous section, with the attached developed procedure for correction of solutions from DLT according to SLT, a wide range of effects, geology, piles, and types of structures which require constructing piles, was statistically considered so that the implementation of the proposed procedure and test results would be as valid and efficient for the following scientific research and practical application. The essence is in the independence of results obtained at different locations by testing in different geological conditions in which piles are constructed. As can be seen, in the proposed procedure, there is no geology parameter, because the goal of the developed procedure is to obtain the solution in compliance with standard EN 1997-1:2004, /5/, independently of the geology parameters, so that the correction procedure can be implemented for other tests on any location, independently even from geometrical characteristics of piles.

Preceding tests on practical examples indicated that by implementation of DLT, slightly higher values of bearing capacity are obtained in relation to SLT results, if the comparison is conducted by the settlement equivalence $s_{DLT}=s_{SLT}$. However, in order to theoretically prove it, the analysis of the relation of bearing capacity of SLT and DLT according to EN 1997-1:2004 /5/ is conducted. When the annex of EN 1997-1:2004 /5/ is observed, in which correlation factors ξ_1 and ξ_2 for SLT are presented, it can be noticed that for ≥ 5 of tested piles, the solution has the highest level of reliability (ξ_1 = 1 and ξ_2 = 1). For a smaller number of piles, it is necessary to correct the solution using correlation factors ξ_1 and ξ_2 greater than 1. The solution for correlation factors ξ_5 and ξ_6 for DLT should be in relation to the solution from SLT, specifically for the situation when $\xi_1 = 1$ and $\xi_2 = 1$. In order to confirm this, several hypotheses are made and analyzed.

HYPOTHESIS 1: BEARING CAPACITIES FROM DLTs ARE LOWER THAN FROM SLT

The average value of bearing capacity $(R_{c,m,DLT})_{mean}$ from DLT is lower than the average value of bearing capacity $(R_{c,m,SLT})_{mean}$ from SLT for the same level of realized settlement $s_{DLT} = s_{SLT}$:

$$(R_{c,m,DLT})_{mean} < (R_{c,m,SLT})_{mean} \,. \tag{20}$$

If the consideration is done for only one SLT, the result is $(R_{c,m,SLT})_{mean} = (R_{c,m,SLT})_{\min} = R_{c,m,SLT}$, so Eq.(6) can be written as:

$$R_{c,d,SLT} = \frac{\min\left\{\frac{(R_{c,m,SLT})_{mean}}{\xi_1};\frac{(R_{c,m,SLT})_{min}}{\xi_2}\right\}}{\gamma_t} = \\ = \frac{\min\left\{\frac{R_{c,m,SLT}}{1.4};\frac{R_{c,m,SLT}}{1.4}\right\}}{\gamma_t} = \frac{\frac{R_{c,m,SLT}}{1.4}}{\gamma_t} \,. \tag{21}$$

Analogous to the previous consideration, for only one DLT, the result is $(R_{c,m,DLT})_{mean} = (R_{c,m,DLT})_{\min} = R_{c,m,DLT}$, so Eq.(7) can be written as:

$$R_{c,d,DLT} = \frac{\min\left\{\frac{(R_{c,m,DLT})_{mean}}{\xi_5};\frac{(R_{c,m,DLT})_{min}}{\xi_6}\right\}}{\gamma_t} = \\ = \frac{\min\left\{\frac{R_{c,m,DLT}}{1.633};\frac{R_{c,m,DLT}}{1.55}\right\}}{\gamma_t} = \frac{\frac{R_{c,m,DLT}}{1.633}}{\gamma_t} \,. \tag{22}$$

Since we started from the assumption formulated by Eq. (20) for the same level of realized settlement $s_{DLT} = s_{SLT}$, i.e., when the analysis is performed for only one SLT and only one DLT, the result is:

$$R_{c,m,DLT} < R_{c,m,SLT} \,. \tag{23}$$

By rearranging Eqs. (21) and (22) and switching them with Eq.(23) the result is:

$$1.633\gamma_t R_{c,d,DLT} < 1.4\gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad 1.166 < \frac{R_{c,d,SLT}}{R_{c,d,DLT}} \,. \tag{24}$$

Since both SLT and DLT, and in-situ soil tests, strive to obtain equal or approximately equal design value of bearing capacity $R_{c,d}$, because it would not make sense to use different methods to obtain considerably different bearing capacities, so, in this sense the right side of Eq.(24) can be conditionally observed as:

$$\frac{R_{c,d,SLT}}{R_{c,d,DLT}} \to 1 \,, \tag{25}$$

so, Eq.(24) becomes:

$$1.166 < 1 \,, \tag{26}$$

which results in an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

If a large number of SLTs and DLTs is considered, based on Eqs. (6) and (7), several options for a more detailed consideration of bearing capacity according to SLT and DLT are obtained. In the first case, what is relevant is $(R_{c,m,SLT})_{mean}$ from SLT, so Eq.(6) becomes:

$$R_{c,d,SLT} = \frac{\frac{(R_{c,m,SLT})_{mean}}{\xi_1}}{\gamma_t} \,. \tag{27}$$

Also, let us take into consideration that $(R_{c,m,DLT})_{mean}$ from DLT is relevant, so Eq.(7) becomes:

$$R_{c,d,DLT} = \frac{\frac{(R_{c,m,DLT})_{mean}}{\xi_5}}{\gamma_t} \,. \tag{28}$$

By rearranging Eqs. (27) and (28) by switching them with Eq.(23) the result is:

$$\xi_5\gamma_t R_{c,d,DLT} < \xi_1\gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_5}{\xi_1} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}} \,. \tag{29}$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_5}{\xi_1} < 1 \,. \tag{30}$$

Values of correlation factor ξ_5, for the same number of tested piles according to SLT and DLT, are higher than the correlation factor ξ_1, so the obtained solution is higher than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with standard EN 1997-1:2004, /5/.

In the second case, what is relevant is $(R_{c,m,SLT})_{mean}$ from SLT, so Eq.(27) is valid. Also, take into consideration that $(R_{c,m,DLT})_{\min}$ from DLT is relevant, so Eq.(7) becomes:

$$R_{c,d,DLT} = \frac{\frac{(R_{c,m,DLT})_{min}}{\xi_6}}{\gamma_t} \,. \tag{31}$$

Considering that we started from the assumption formulated by Eq.(20) for the same level of realized settlement $s_{DLT} = s_{SLT}$, the following expression should also hold:

$$(R_{c,m,DLT})_{min} < (R_{c,m,SLT})_{mean} \,. \tag{32}$$

By rearranging Eqs. (27) and (31) and switching them with Eq.(32) the result is:

$$\xi_6\gamma_t R_{c,d,DLT} < \xi_1\gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_6}{\xi_1} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}} \,. \tag{33}$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_6}{\xi_1} < 1 \,. \tag{34}$$

Values of correlation factor ξ_6, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_1, so the obtained solution is larger than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

In the third case we have what is relevant $(R_{c,m,SLT})_{\min}$ from SLT, so the Eq.(6) becomes:

$$R_{c,d,SLT} = \frac{\dfrac{(R_{c,m,SLT})_{min}}{\xi_2}}{\gamma_t} . \qquad (35)$$

Now, let us take into account that $(R_{c,m,DLT})_{mean}$ from DLT is relevant, so Eq.(28) holds. When:

$$(R_{c,m,DLT})_{mean} < (R_{c,m,SLT})_{\min} , \qquad (36)$$

the result is:

$$\xi_5 \gamma_t R_{c,d,DLT} < \xi_2 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_5}{\xi_2} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (37)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_5}{\xi_2} < 1 . \qquad (38)$$

Values of correlation factor ξ_5, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_2, so the obtained solution is larger than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/. If:

$$(R_{c,m,DLT})_{mean} > (R_{c,m,SLT})_{\min} , \qquad (39)$$

the result is:

$$\xi_5 \gamma_t R_{c,d,DLT} > \xi_2 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_5}{\xi_2} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (40)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_5}{\xi_2} > 1 . \qquad (41)$$

Values of correlation factor ξ_5, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_2, so the obtained solution is larger than 1, which is in fact a correct solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/, however, the question is whether it is possible to have such a situation in reality.

In the fourth case we have what is relevant $(R_{c,m,SLT})_{\min}$ from SLT, so Eq.(35) holds. Now, let us take into account that $(R_{c,m,DLT})_{\min}$ from DLT is relevant, so Eq.(31) holds. When:

$$(R_{c,m,DLT})_{\min} < (R_{c,m,SLT})_{\min} , \qquad (42)$$

the result is:

$$\xi_6 \gamma_t R_{c,d,DLT} < \xi_2 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_6}{\xi_2} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (43)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_6}{\xi_2} < 1 . \qquad (44)$$

Values of correlation factor ξ_6, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_2, so the obtained solution is larger than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

HYPOTHESIS 2: BEARING CAPACITIES FROM DLTs ARE APPROXIMATELY IDENTICAL TO BEARING CAPACITIES FROM SLT

The average value of bearing capacity $(R_{c,m,DLT})_{mean}$ from DLT is approximately identical to the average value of bearing capacity $(R_{c,m,SLT})_{mean}$ from SLT for the same level of realized settlement $s_{DLT} = s_{SLT}$:

$$(R_{c,m,DLT})_{mean} \approx (R_{c,m,SLT})_{mean} . \qquad (45)$$

If the consideration is done for only one SLT, the result is $(R_{c,m,SLT})_{mean} = (R_{c,m,SLT})_{\min} = R_{c,m,SLT}$, so Eq.(21) holds. Analogous to the previous consideration, for only one DLT, the result is $(R_{c,m,DLT})_{mean} = (R_{c,m,DLT})_{\min} = R_{c,m,DLT}$, so Eq.(22) holds. Since we started from the assumption formulated by Eq.(45) for the same level of realized settlement $s_{DLT} = s_{SLT}$, i.e., when the analysis is performed for only one SLT and only one DLT, the result is:

$$R_{c,m,DLT} \approx R_{c,m,SLT} . \qquad (46)$$

Switching Eqs. (21) and (22) with Eq.(46) results in:

$$1.633 \gamma_t R_{c,d,DLT} \approx 1.4 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad 1.166 \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (47)$$

Since both SLT and DLT and in-situ soil tests, strive to obtain equal or approximately equal design value of bearing capacity $R_{c,d}$, because it would not make sense to use different methods to obtain considerably different bearing capacities, so in this sense the right side of Eq.(47) can be conditionally observed according to Eq.(25), so Eq.(47) becomes:

$$1.166 \approx 1 , \qquad (48)$$

which is an incorrect solution in the mathematical sense and in compliance with the standard EN 1997-1:2004, /5/.

If a large number of SLTs and DLTs is considered, based on Eqs. (6) and (7), several options for a more detailed consideration of bearing capacity according to SLT and DLT are obtained. In the first case, what is relevant is $(R_{c,m,SLT})_{mean}$ from SLT, so Eq.(27) holds. Also, let us take into account that $(R_{c,m,DLT})_{mean}$ from DLT is relevant, so Eq.(28) holds. Switching Eqs. (27) and (28) with Eq.(45) results in:

$$\xi_5 \gamma_t R_{c,d,DLT} \approx \xi_1 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_5}{\xi_1} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (49)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_5}{\xi_1} \approx 1 . \qquad (50)$$

Values of the correlation factor ξ_5, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_1, so the obtained solution is larger than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

In the second case we have that what is relevant $(R_{c,m,SLT})_{mean}$ from SLT, so Eq.(27) holds. Now, let us take into account that $(R_{c,m,DLT})_{\min}$ from DLT is relevant, so Eq. (31) holds. Since we started from the assumption formulated by Eq.(45) for the same level of realized settlement $s_{DLT} = s_{SLT}$, the following expression should also hold:

$$(R_{c,m,DLT})_{\min} \approx (R_{c,m,SLT})_{mean} . \qquad (51)$$

Switching Eqs. (27) and (31) with Eq.(51) results in:

$$\xi_6 \gamma_t R_{c,d,DLT} \approx \xi_1 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_6}{\xi_1} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (52)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_6}{\xi_1} \approx 1 . \qquad (53)$$

Values of the correlation factor ξ_6, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_1, so the obtained solution is larger than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

In the third case we have that what is relevant $(R_{c,m,SLT})_{\min}$ from SLT, so Eq.(35) holds. Now, let us take into account that $(R_{c,m,DLT})_{mean}$ from DLT is relevant, so Eq.(28) holds. When:

$$(R_{c,m,DLT})_{mean} \approx (R_{c,m,SLT})_{\min} , \qquad (54)$$

the result is:

$$\xi_5 \gamma_t R_{c,d,DLT} \approx \xi_2 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_5}{\xi_2} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (55)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_5}{\xi_2} \approx 1 . \qquad (56)$$

Values of the correlation factor ξ_5, for the same number of tested piles according to SLT and DLT, are greater than correlation factor ξ_2, so the obtained solution is larger than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

In the fourth case we have that what is relevant $(R_{c,m,SLT})_{\min}$ from SLT, so Eq.(35) holds. Now, let us take into account that $(R_{c,m,DLT})_{\min}$ from DLT is relevant, so Eq.(31) holds. When:

$$(R_{c,m,DLT})_{\min} \approx (R_{c,m,SLT})_{\min} , \qquad (57)$$

the result is:

$$\xi_6 \gamma_t R_{c,d,DLT} \approx \xi_2 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_6}{\xi_2} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (58)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_6}{\xi_2} \approx 1 . \qquad (59)$$

The values of correlation factor ξ_6, for the same number of tested piles according to SLT and DLT, are greater than correlation factor ξ_2, so the obtained solution is larger than 1, which is in fact an incorrect solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

HYPOTHESIS 3: BEARING CAPACITIES FROM DLTs ARE HIGHER THAN BEARING CAPACITIES FROM SLT

The average value of bearing capacity $(R_{c,m,DLT})_{mean}$ from DLT is higher than the average value of bearing capacity $(R_{c,m,SLT})_{mean}$ from SLT for the same level of realized settlement $s_{DLT} = s_{SLT}$:

$$(R_{c,m,DLT})_{mean} > (R_{c,m,SLT})_{mean} . \qquad (60)$$

If the consideration is done for only one SLT, the result is $(R_{c,m,SLT})_{mean} = (R_{c,m,SLT})_{\min} = R_{c,m,SLT}$, so Eq.(21) holds. Analogous to the previous consideration, for only one DLT, the result is $(R_{c,m,DLT})_{mean} = (R_{c,m,DLT})_{\min} = R_{c,m,DLT}$, so Eq.(22) holds. Since we started from the assumption formulated by Eq.(60) for the same level of realized settlement $s_{DLT} = s_{SLT}$, i.e., when analysis is performed for only one SLT and only one DLT, the result is:

$$R_{c,m,DLT} > R_{c,m,SLT} . \qquad (61)$$

Switching Eqs. (21) and (22) with Eq.(61) results in:

$$1.633 \gamma_t R_{c,d,DLT} > 1.4 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad 1.166 > \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (62)$$

Since both SLT and DLT and in-situ soil tests, strive to obtain equal or approximately equal design value of bearing capacity $R_{c,d}$, because it would not make sense to use different methods to obtain considerably different bearing capacities, so in this sense the right side of Eq.(62) can be conditionally observed according to Eq.(25), so Eq.(62) now becomes:

$$1.166 > 1 , \qquad (63)$$

which is a correct solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

If a large number of SLTs and DLTs is considered, based on Eqs. (6) and (7) several options for a more detailed consideration of bearing capacity according to SLT and DLT are obtained. In the first case we have what is relevant $(R_{c,m,SLT})_{mean}$ from SLT, so Eq.(27) holds. Also, let us take into account that $(R_{c,m,DLT})_{mean}$ from DLT is relevant, so Eq.(28) holds. Switching Eqs. (27) and (28) with Eq.(60) results in:

$$\xi_5 \gamma_t R_{c,d,DLT} > \xi_1 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_5}{\xi_1} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (64)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_5}{\xi_1} > 1 . \qquad (65)$$

Values of the correlation factor ξ_5, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_1, so the obtained solution is larger than 1, which is in fact a correct solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

In the second case we have what is relevant $(R_{c,m,SLT})_{mean}$ from SLT, so Eq.(27) holds. Now, let us take into account that $(R_{c,m,DLT})_{\min}$ from DLT is relevant, so Eq.(31) holds. Since we started from the assumption formulated by Eq. (60) for the same level of realized settlement $s_{DLT} = s_{SLT}$, the following expression should hold:

$$(R_{c,m,DLT})_{\min} > (R_{c,m,SLT})_{mean} . \qquad (66)$$

Switching Eqs. (27) and (31) with Eq.(66) results in:

$$\xi_6 \gamma_t R_{c,d,DLT} > \xi_1 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_6}{\xi_1} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}} . \qquad (67)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_6}{\xi_1} > 1 . \qquad (68)$$

Values of correlation factor ξ_6, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_1, so the obtained solution is larger than 1, which is in fact a correct solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

In the third case we have that what is relevant $(R_{c,m,SLT})_{\min}$ from SLT, so Eq.(35) holds. Now, let us take into account that $(R_{c,m,DLT})_{mean}$ from DLT is relevant, so Eq.(28) holds. When:

$$(R_{c,m,DLT})_{mean} > (R_{c,m,SLT})_{\min}, \qquad (69)$$

the result is:

$$\xi_5 \gamma_t R_{c,d,DLT} > \xi_2 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_5}{\xi_2} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}}. \qquad (70)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_5}{\xi_2} > 1. \qquad (71)$$

The values of correlation factor ξ_5, for the same number of tested piles according to SLT and DLT, are greater than correlation factor ξ_2, so the obtained solution is larger than 1, which is in fact a correct solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/.

In the fourth case we have what is relevant $(R_{c,m,SLT})_{\min}$ from SLT, so Eq.(35) holds. Now, let us take into account that $(R_{c,m,DLT})_{\min}$ from DLT is relevant, so Eq.(31) holds. When:

$$(R_{c,m,DLT})_{\min} > (R_{c,m,SLT})_{\min}, \qquad (72)$$

the result is:

$$\xi_6 \gamma_t R_{c,d,DLT} > \xi_2 \gamma_t R_{c,d,SLT} \quad \text{i.e.,} \quad \frac{\xi_6}{\xi_2} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}}. \qquad (73)$$

Taking into consideration the rule from Eq.(25), the following expression is obtained:

$$\frac{\xi_6}{\xi_2} > 1. \qquad (74)$$

Values of the correlation factor ξ6, for the same number of tested piles according to SLT and DLT, are greater than the correlation factor ξ_2, so the obtained solution is larger than 1, which is in fact a correct solution in the mathematical sense and in compliance with EN 1997-1:2004, /5/. Table 3 shows the recapitulation of the considered analyses and obtained solutions. As it can be seen, based on conducted analyses, the statement mentioned in the scientific paper: *After analyzing all diagrams, it can be stated that by using DLT, slightly higher values are obtained in comparison to SLT results, if the comparison is conducted using the settlement equivalence* $s_{DLT} = s_{SLT}$ - has been mathematically presented and proven. Generally speaking, it is possible to obtained in practice all presented and considered situations, but the research presented here indicates that generally a slightly higher mobilized static bearing capacity is obtained from DLT than from SLT, which corresponds to the methodology of calculation of pile bearing capacity shown in the standard EN 1997-1:2004, /5/.

Table 3. Recapitulation of considered analyses and obtained solutions.

no. of tests (tested piles)		condition – attitude	solution		statement
analysis 1 (DLT<SLT)					
SLT=1 and DLT=1		$R_{c,m,mean,DLT} < R_{c,m,mean,SLT}$	$1.166 < \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$1.166 < 1$	incorrect solution
SLT>1 DLT>1	**1**	$R_{c,m,mean,DLT} < R_{c,m,mean,SLT}$	$\frac{\xi_5}{\xi_1} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_5}{\xi_1} < 1$	incorrect solution
	2	$R_{c,m,min,DLT} < R_{c,m,mean,SLT}$	$\frac{\xi_6}{\xi_1} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_6}{\xi_1} < 1$	incorrect solution
	3	$R_{c,m,mean,DLT} < R_{c,m,min,SLT}$	$\frac{\xi_5}{\xi_2} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_5}{\xi_2} < 1$	incorrect solution
	4	$R_{c,m,min,DLT} < R_{c,m,min,SLT}$	$\frac{\xi_6}{\xi_2} < \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_6}{\xi_2} < 1$	incorrect solution
analysis 2 (DLT≈SLT)					
SLT=1 and DLT=1		$R_{c,m,mean,DLT} \approx R_{c,m,mean,SLT}$	$1.166 \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$1.166 \approx 1$	incorrect solution
SLT>1 DLT>1	**1**	$R_{c,m,mean,DLT} \approx R_{c,m,mean,SLT}$	$\frac{\xi_5}{\xi_1} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_5}{\xi_1} \approx 1$	incorrect solution
	2	$R_{c,m,min,DLT} \approx R_{c,m,mean,SLT}$	$\frac{\xi_6}{\xi_1} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_6}{\xi_1} \approx 1$	incorrect solution
	3	$R_{c,m,mean,DLT} \approx R_{c,m,min,SLT}$	$\frac{\xi_5}{\xi_2} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_5}{\xi_2} \approx 1$	incorrect solution
	4	$R_{c,m,min,DLT} \approx R_{c,m,min,SLT}$	$\frac{\xi_6}{\xi_2} \approx \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_6}{\xi_2} \approx 1$	incorrect solution
analysis 3 (DLT>SLT)					
SLT=1 and DLT=1		$R_{c,m,mean,DLT} > R_{c,m,mean,SLT}$	$1.166 > \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$1.166 > 1$	correct solution
SLT>1 DLT>1	**1**	$R_{c,m,mean,DLT} > R_{c,m,mean,SLT}$	$\frac{\xi_5}{\xi_1} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_5}{\xi_1} > 1$	correct solution
	2	$R_{c,m,min,DLT} > R_{c,m,mean,SLT}$	$\frac{\xi_6}{\xi_1} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_6}{\xi_1} > 1$	correct solution
	3	$R_{c,m,mean,DLT} > R_{c,m,min,SLT}$	$\frac{\xi_5}{\xi_2} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_5}{\xi_2} > 1$	correct solution
	4	$R_{c,m,min,DLT} > R_{c,m,min,SLT}$	$\frac{\xi_6}{\xi_2} > \frac{R_{c,d,SLT}}{R_{c,d,DLT}}$	$\frac{\xi_6}{\xi_2} > 1$	correct solution

IMPLEMENTATION OF THE PROCEDURE

Based on the previously developed procedure, bearing capacities obtained from DLTs are corrected according to SLT results in seven considered tests. The calculation of the bearing capacity correction $R_{c,m,DLT/SLT}$ obtained from DLT according to SLT is performed according to Eqs. (13) and (14), taking into consideration Eq.(16).

The average deviation of bearing capacity from DLT according to SLT, when calculation is performed using the correction coefficient c_{mean} (ξ_5 = 1.633), is up to Δm = 8.04 %. The average deviation of bearing capacity from DLT according to SLT, when calculation is conducted using correction coefficient $c_{\min}$ (ξ_6 = 1.55), is up to Δm = 3.1 %. It can be concluded that the correction coefficient c_{min} is relevant for bearing capacity correction $R_{c,m,DLT/SLT}$ from DLT according to SLT. The values of correlation factors ξ_5 and ξ_6, as already explained, were determined by extrapolation of correlation factor values for multiple piles according to standard EN 1997-1:2004, /5/.

Iterating correlation factors ξ_5 and ξ_6, since they participate in correction coefficients c_{mean} and $c_{\min}$, determines the values where the least deviation is obtained from corrected bearing capacity values $R_{c,m,DLT/SLT}$ from DLT in comparison to the solution according to SLT. The iterated value of the correlation factor is $\xi_5 = \xi_6$ = 1.51, while the average deviation of bearing capacity from DLT according to SLT is Δm = 1.57 %. Iterations could not produce an even smaller deviation. Figure 17 shows the variation of correlation factors ξ_5 and ξ_6 in the function of DLT solution deviation as percent in comparison to SLT solutions. The optimal solution corresponds to the minimum of DLT solution deviation as percentage in comparison to SLT solutions. The comparison of corrected bearing capacities $R_{c,m,DLT/SLT}$ from DLT, according to the previously developed procedure for correction coefficient $c_{\min}$ (ξ_6 = 1.55) and taking into consideration the iteration of correlation factors $\xi_5 = \xi_6$ = 1.51, with interpolated forces $P_{int,SLT}$ from SLT, for the same level of settlement $s_{DLT} = s_{SLT}$, is shown in Fig. 18.

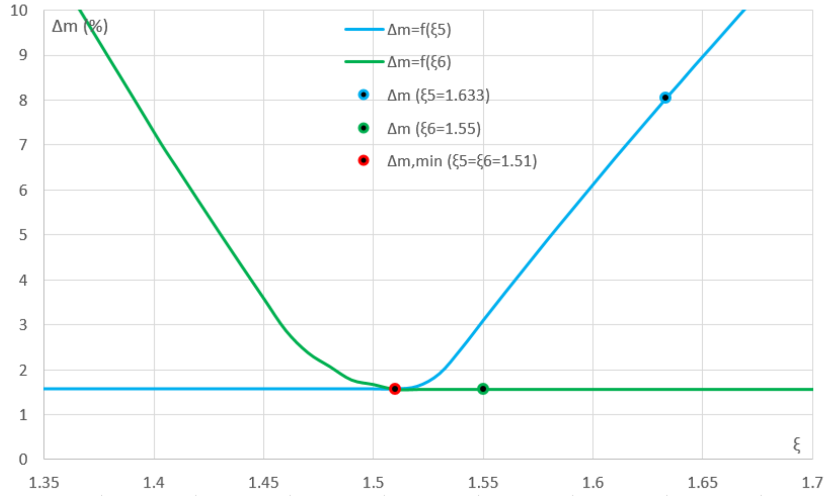
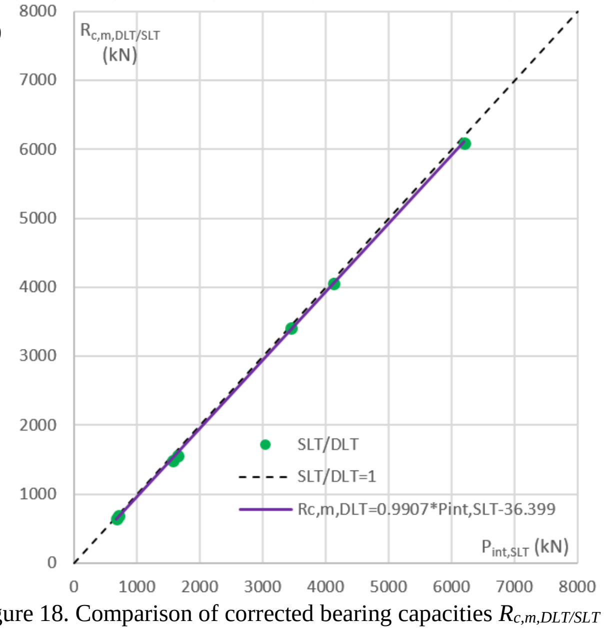


Figure 17. Variation of correlation factors ξ_5 and ξ_6 in function of the DLT solution deviation in comparison to SLT solutions.

a)



b)

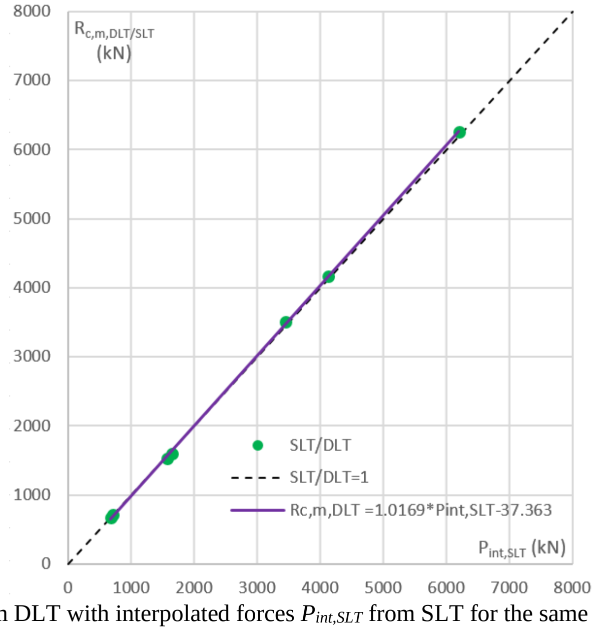
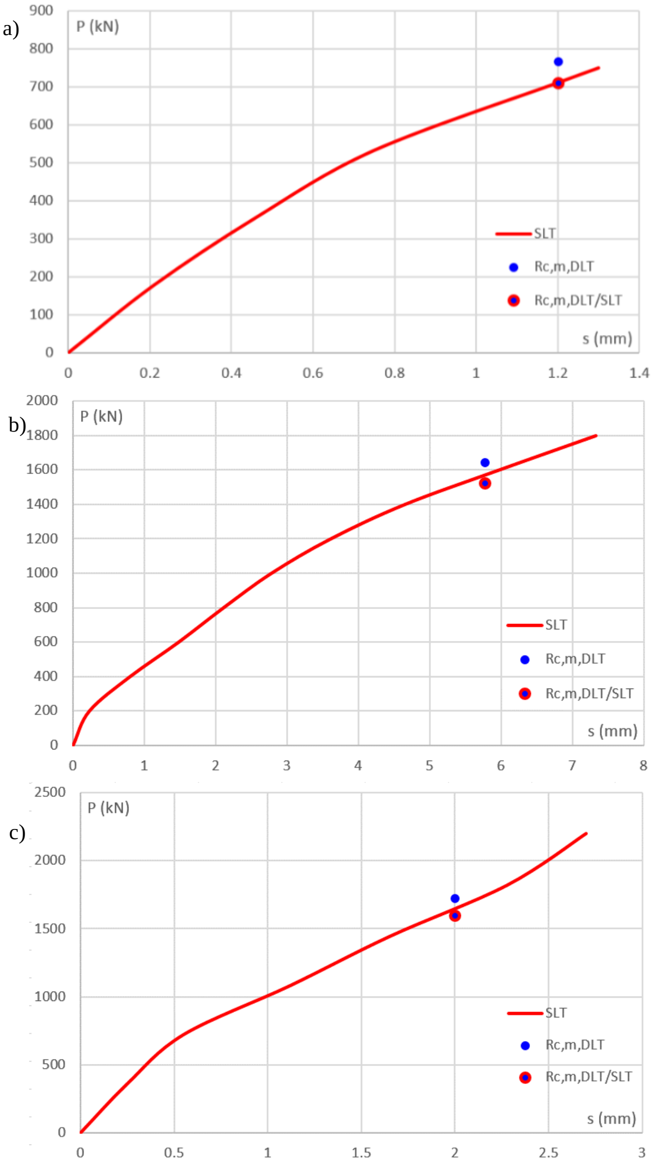


Figure 18. Comparison of corrected bearing capacities $R_{c,m,DLT/SLT}$ from DLT with interpolated forces $P_{int,SLT}$ from SLT for the same level of settlement $s_{DLT} = s_{SLT}$: a) according to previously developed procedure for correction coefficient c_{min} (ξ_6 = 1.55); b) taking into consideration correlation factors $\xi_5 = \xi_6$ = 1.51 iterations.

In the first case, for correction coefficient c_{min} (ξ_6 = 1.55), regression analysis is conducted for linear function $R_{c,m,DLT/SLT}$ = 0.9907$P_{int,SLT}$ – 36.399 and the determination coefficient r^2 = 0.9998. In the second case, taking into consideration the iteration of correlation factors ξ_5 = ξ_6 = 1.51, the regression analysis is conducted for linear function $R_{c,m,DLT/SLT}$ = 1.0169$P_{int,SLT}$ – 37.363 and the determination coefficient r^2 = 0.9998. It is evident that the corrected solution (ξ_5 = ξ_6 = 1.51) is in excellent agreement with the ideal situation SLT/DLT = 1.

Figure 19 shows test load curves of SLT of piles, with mobilized static bearing capacity $R_{c,m,DLT}$ obtained from DLT of piles, with corrected mobilized static bearing capacity of piles $R_{c,m,DLT/SLT}$ from DLT according to the previously developed procedure and taking into consideration the iteration of correlation factors ξ_5 = ξ_6 = 1.51.

After analyzing all diagrams, it can be stated that now more substantially corrected values of bearing capacity $R_{c,m,DLT}$ are obtained from DLT, so the deviations of solutions of DLT in comparison to solutions from SLT are generally smaller.



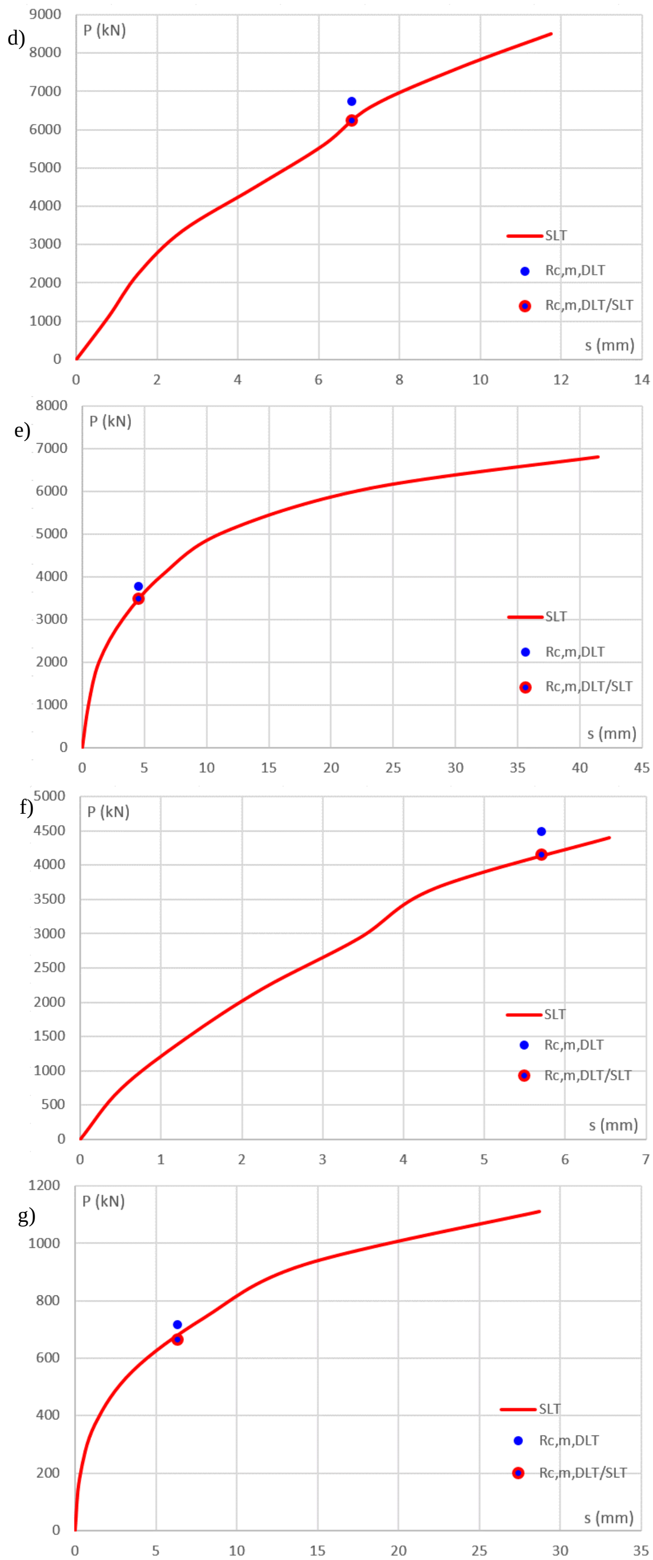


Figure 19. Test load curves of SLT of piles, mobilized static bearing capacity $R_{c,m,DLT}$ obtained from DLT of piles, corrected mobilized static bearing capacity of piles $R_{c,m,DLT/SLT}$ from DLT according to previously developed procedure and taking into consideration the iteration of correlation factors ξ_5 = ξ_6 = 1.51, piles: a) no.1, b) no.2, c) no.3, d) no. 4, e) no.5, f) no.6, g) no.7.

CONCLUSIONS

The developed and presented procedure, for correction of solutions from DLT according to SLT, is based on the facts that the correction is carried out independently of:
- dimensions (diameter and length) of the pile,
- technological model of the pile,
- geology in which the pile is built.

Also, when developing the procedure for correction of solutions from DLT according to SLT, the following facts were the starting point:
- that already existing and proven methods for the analysis of mobilized static bearing capacity from DLTs are used (signal matching method, wave theory, and method of characteristics),
- that the developed procedure is based on EN 1997-1:2004 /5/ according to calculations of pile bearing capacity from SLT and DLT, and correlation factors ξ_1, ξ_2, ξ_5 and ξ_6,
- that the developed procedure is simple for practical use, but sufficiently reliable, which has been proven, because when using this procedure, the obtained deviation of solutions from DLT according to SLT is 1.57 %.

Based on the research conducted in this paper, through comparative analysis and correction of bearing capacity of piles examined by DLT according to SLT, the following conclusions are drawn:
- the average deviation of bearing capacity from DLT, according to SLT is $\Delta_m = 7.29$ %,
- after analyzing presented diagrams, it can be stated that by using DLT, slightly higher values are obtained in comparison to SLT results, if the comparison is conducted using the settlement equivalence $s_{DLT} = s_{SLT}$,
- the regression analysis of the linear function, provided the statistical model of variation of bearing capacity from DLT according to SLT, whereby it is evident that for higher bearing capacities from DLT result a slightly higher deviation in comparison to the solution from SLT of piles,
- the procedure for the correction of bearing capacity solutions from DLT according to SLT has been developed, in compliance with the provisions of EN 1997-1:2004, /5/,
- the regression analysis of the linear function, for the developed solution correction procedure has provided the statistical model of the variation of bearing capacity from DLT according to SLT which exhibits a fairly better agreement with the ideal situation SLT/DLT = 1,
- the average deviation of bearing capacity, according to the developed procedure of solution correction for c_{min} ($\xi_6 = 1.55$), from DLT according to SLT is up to $\Delta_m = 3.1$ %,
- the iteration of correlation factor values up to $\xi_5 = \xi_6 = 1.51$, produced deviation values of the corrected bearing capacities from DLT according to SLT, up to $\Delta_m = 1.57$ %.

The results for one DLT and one SLT for each location are presented. When the testing problem is considered for one DLT, the correlation factors, according to EN 1997-1:2004 /5/ are the highest, which indicates a low degree of reliability of solutions. The research is intentionally conducted for only one DLT and one SLT, so that for such a low degree of reliability of solutions, observing only one DLT for each location, the presented procedure of correction of solutions from DLT according to SLT would provide the final solution with a very high degree of reliability.

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