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STRAIN MEASUREMENTS DURING STATIC PILE TESTING: A CASE STUDY OF TWO PILES WITH DIFERENT DIAMETER AND LENGTH

Abstract

The paper presents testing of two piles, diameter of Ø1200mm and Ø800mm, length of 26.0m and 18.0m respectively. Tests were conducted on construction project WELLPORT III phase - New Belgrade, Republic of Serbia. The piles were erected using CFA technology by Novkol jsc. - Belgrade. The tests were conducted according to the standard SRPS EN ISO 22477-1: 2019, jointly by the Laboratory for structures of the Faculty of Civil Engineering University of Belgrade and Laboratory of Novkol jsc. - Belgrade. In addition, beside to the common and inevitable measurement of pile settlement with respect to the applied load during test phases, tests include measurements of strain along the pile depth. Measurements of strain were carried using so-called 'sister-bar' based on resistance principle (classical foil strain gages), as well as using embedded sensors based on 'vibrating-wire' principle of strain measurement, as both principles of strain measurements are state-off-the-art in actual practice. Installation of all instruments were incorporated in pile reinforcement assembly at several levels before casting. During testing, beside to recording force at pile head and settlements by LVDTs which were leaned on the reference beam, there were recorded and realized strain levels on all installed instruments. During data reduction phase, computation of actual force was realized at each section with strain measurement, based on axial stiffness of tested piles. Using such a procedure, forces in tested piles were calculated. Such data gave possibility to explore part of force which was transmitted by pile shaft along the depth to the surrounding soil, as well as the part which goes to the pile base. All results are shown in illustrative diagrams of corresponding stresses between pile shaft and surrounding soil, force levels along the pile depth, and finally level of force which transfer by pile shaft and pile base. According to the facts that pile bases were in different soil level, and with different diameters, the different ratio between force levels which transferred by pile shaft and pile base were established.

Keywords

Pile testing, pile settlement, pile strain measurement, pile skin force, pile base force.

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1. INTRODUCTION

During pile load testing, as the most important indication of the pile response is to observe pile head settlement in respect to the applied load, which is relevant for the estimation of pile bearing capacity and judge satisfaction of serviceability limit state. According to the current practice in Republic of Serbia pile tests are performed according to standard SRPS EN ISO 22477-1:2019 [1].

According to trends in order to acquire more precisely data of load transfer from pile shaft to soil, strain measurements along pile is being used [5,6,7], and different types of sensors are being used for such purposes. In Figure 1 are shown commonly used sensors produced by *Geokon Inc.* USA. So called 'sister-bar' rebar strain meters, based on vibrating wire or resistance principle of strain measurements, are the most suitable for application cast-in-place concrete piles, because they are rugged and it is easier to maintain alignment along the pile axis [7], Figure 1. The second type of sensors, 'embedded-type' sensors mainly based on vibrating wire principle of strain measurement are more suitable for application in precast piles, Figure 1.

Figure 1. Vibrating Wire 'sister-bar' (left), Resistance 'sister-bar' (middle), Vibrating Wire 'embedded' sensor (right) – Geokon Inc. USA [8]

For application of all types, sensors have to take a care about sensor alignment and sensor and cable protection, with respect to not damage it during piles execution. Protection and alignment of "sister" bars is easier than "embedment" sensors, especially during application of cast-in-place concrete piles, where it has to be protected to avoid a damage, using the most appropriate solution. With respect to cable protection, suggestion is that the cables have to be tied to the longitudinal bars at about 2-meter spacing [5].

2. LAYOUTS AND INSTRUMENTATION OF TESTED PILES

Two piles, pile-T1 with diameter of 1200mm and length of 26m and pile-T2 with diameter of 800mm and length of 18m on site *WELLPORT-III* in Belgrade, were instrumented and tested in November 2021, 21 days after pile execution by *Novkol jsc.* using CFA technology. In Figure 2 are shown layouts of strain gauge installations along pile's depth with appropriate geotechnical profile of soil layers. Pile base of pile T2 (elevation of 50.10m a.s.l.) were in soil layer of silty sand with sand-stone debris and pile base of longer pile T1 lies in soil layer of river lake clay (elevation of 42.00m a.s.l.). Also, the top of the both piles were practically at the same level, +68.00 ASL (above the sea level), Figure 2.

In the case of pile-T1 sensors were placed in five cross sections, Pr-1/2/3/4/5 at mutual equidistant of 5.0m, while in the case of pile-T2 four cross sections were placed at mutual equidistant of 4.0m, Pr-1/2/3/4 Figure 2.

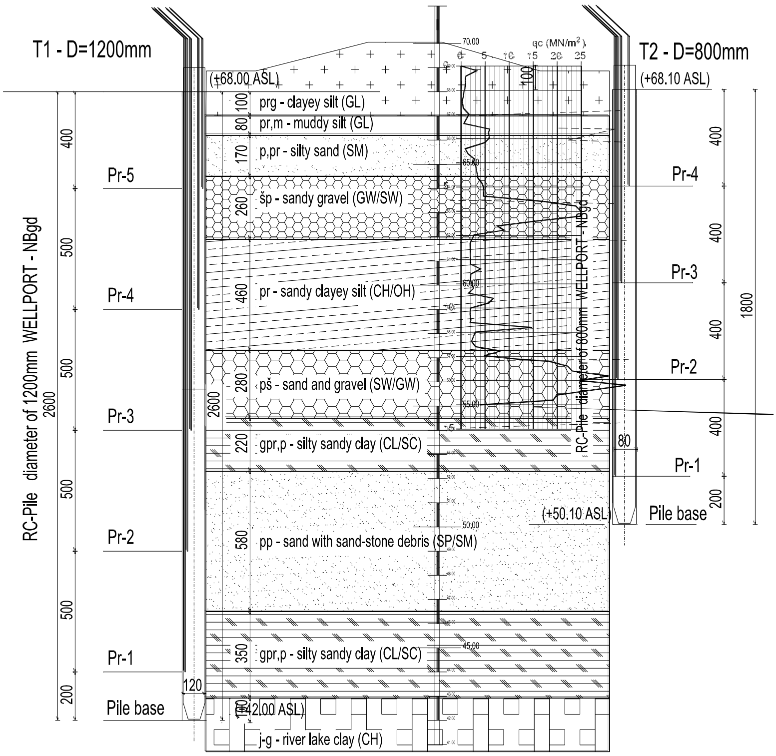

Figure 2. Setup of strain measurement tested piles T1 and T2 with geotechnical profile of soil

All cross sections of both piles were instrumented with two embedded sensors for strain measurement based on vibrating wire principle and one ‘sister-bar’ specially made using classical electro-resistant strain gages. Three instruments are radially arranged at a cross-section on radial angle distance of 120 arch-degrees. The cables of all three instruments were routed through a plastic hose outside the reinforcement assembly, and independently for each cross-section installed, Figure 3.

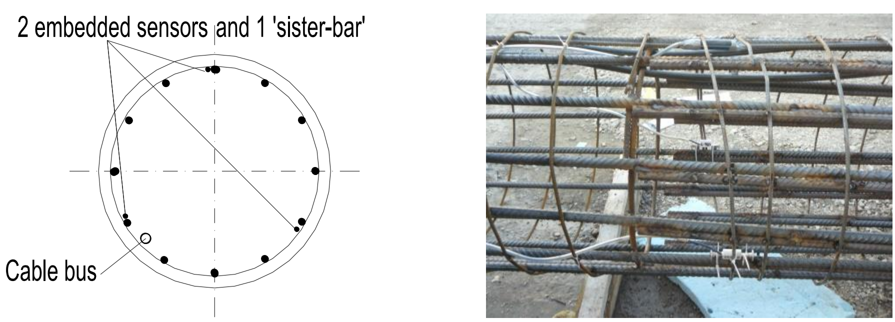

Figure 3. Arrangement of sensors at instrumented cross-sections of tested piles T1 and T2

3. TEST PROCEDURE, LOADS AND MEASUREMENTS

Testing of piles were carried out according to *Method statement* prepared by *Novkol jsc.*, in compliance to [1], which includes additional test procedure of piles and soil (CPT, PIT, Dynamic testing), as well as strain measurements along the piles in addition. In both cases, testing of piles performed using four anchor piles with main and secondary beams, as it is shown in Figure 4.

Figure 4. Photos on-site installations of testing piles T1 (left) and T2 (right)

In both cases tests were carried out during eight phases up to maximum load, and four phases of unloading. Table 1 shows test-load service and maximum loads for both tested piles T1 and T2. Also, for the maximum load level, the equivalent stresses (according to equivalent cross-section area which includes reinforcement) of 6.40 MPa and 5.20 MPa were reached, respectively for the pile-T1 and pile-T2. Should be noted that the maximum load steps produce relatively low level of axial stress on the top of piles. Accordingly, to experience from previously tested piles, it has been reached stress level on pile top up to 10.0 MPa, with the similar ratio of maximum/service load of 1.50. So, according to requirements and corresponding Method statement, relatively low level of stresses realized on the top of tested piles T1 and T2.

	Service load	Maximum load	Maximum / Service	Equivalent top stress
	(kN)	(kN)	(ratio)	(MPa)
Pile T1 D=1200mm	4820	7230	1.50	6.40
Pile T2 D=800mm	1744	2616	1.50	5.20

Table 1. Test load protocol of tested piles T1 and T2

During both piles testing, loading was performed in eight, practically equal load steps up to maximal load levels, while unloading was carried out in four steps, all in accordance to [1,2].

Main measurements include measurements of pile settlement and applied force at one of hydraulic jacks for loading (which has been controlled according to pressure on hydraulic jacks, four in the case of pile-T1 and two in the case of pile-T2). Measurements of settlement were performed using LVDTs supported on so-called reference beam, while force measurements were carried out using load cell with capacity up to 3000 kN, placed above of one of hydraulic jacks applied for loading during testing, Figure 4.

In addition to the above measurements, measurements of strains (secondary measurements) in five/four measuring cross-sections, respectively in the case of pile-T1 and the pile-T2, at three positions at each cross-section were also performed. Measurements were performed using data–loggers for vibrating wire sensors, and measuring amplifier for strain gauges 'sister-bars'.

Readings of all installed sensors and load cell were carried out in accordance to [1,2].

4. DATA REDACTION OF RECORDED RESPONSES

Data redaction of recorded responses was performed according to main measurements (settlement with respect to applied load) and secondary measurements (strain measurements with respect to applied load).

Figure 5 shows settlement piles with respect to applied load steps during testing.

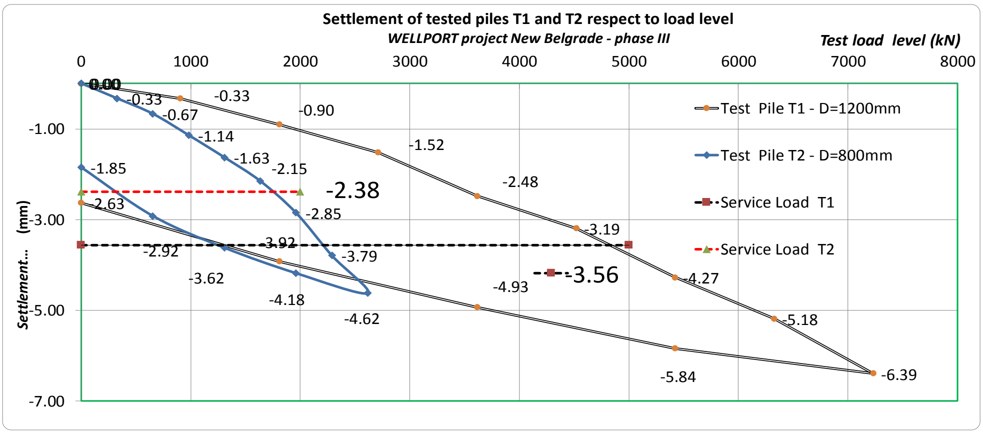

Figure 5. Settlements of tested piles T1 and T2 with respect to applied loads

Recorded settlements for the maximum load steps were 6.39mm and 4.62mm, respectively in the case of pile T1 and T2. Precisely determination of the load bearing capacity is not in the scope of this paper, and which could be estimated on several actual methods, as it is described in [9], for example. The stated values of maximal settlement are 0.52% and 0.58% of the diameter of the corresponding tested pile. The suggestion, according to *Wilteman at. all.* [10], is that the ultimate bearing capacity has been reached on the level of settlement in the range of 5% - 10% of pile diameter. So, there is evident that tested piles have load bearing capacity with satisfactory safety factor, because the maximum level of applied loads are more than 150% of appropriate service load levels. Also, recorded settlements for the service load level are in the range of 3.5 mm, could be concluded that serviceability limit state is also satisfied in the case of both tested piles.

More interesting point of the study is force distribution along depth of tested piles. It stars with computation of relevant strains at each sections of tested piles.

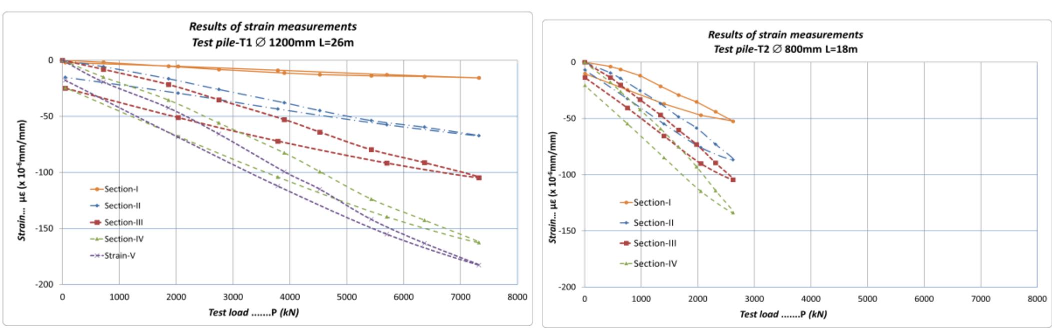

Figure 6. Relevant strains at measuring sections of tested piles T1 and T2

Diagrams of strains shown in Figure 6 represent *relevant strains* at each section according to layout Figure 2, computed as mean-values of all three recorded strains (at one strain level) on installed sensors during testing.

Further analyses include computation of forces at measuring sections based on *relevant strains*. Computations were conducted according to equivalent axial stiffness of piles including reinforcement, as well as modulus of elastic of concrete of E_{con} = 31.5 GPa which corresponds to the reported concrete quality achieved during construction of tested piles, [3,4].

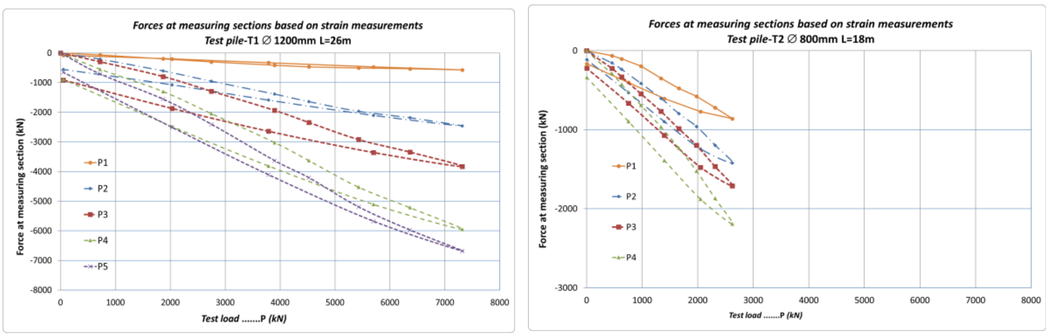

Figure 7. Computed force distribution at measuring sections of tested piles T1 and T2

Based on computed force distributions shown in Figure 7, shear stresses between pile-top and measuring sections (unit shaft friction of soil), with appropriate extrapolation of stresses between *Section-I* and pile base, was computed for the both instrumented and tested piles T1 and T2. Diagrams of such stresses are shown in Figure 8, which represents force transfer between piles and surrounding soil. Changes of shear stress are shown for each test load phase, up to the most relevant test load *phase-VIII*, which corresponds to the maximal test load step for both tested piles. Unloading test phases, because of short time for stabilization of strain readings are excluded from analysis. In the case of pile T1, according to diagrams in Figure 8, is established higher levels of shear stresses (unit frictions of soil). Most likely it is consequence of realized higher level of displacement in particular test phase, caused of shear mobilization between the pile shaft and surrounding soil.

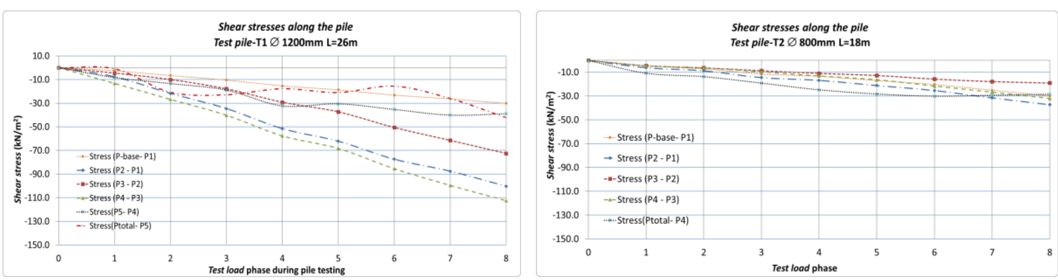

Figure 8. Computed shear stresses between tested piles T1 and T2 and surrounding soil (Unit shaft friction)

Based on known forces at measuring sections, as well as computed shear stresses between pile and surrounding soil between relevant sections, the data for the implementation of the calculated distribution of forces according to the depth of the tested piles were completed.

In Figure 9 are shown axial force distributions along depth of both tested piles T1 and T2. The diagrams are shown at the same scale, so comparison of the results can be made. In the case of tested pile T2 distribution of axial force along pile depth is close to linear, while in the case of pile T1 distribution is quite nonlinear. Most likely, this is a consequence of the higher level of realized settlement in the case of the pile T1 and higher level of shear stresses due to the mobilization of the surrounding soil, as well as the realized higher level of stress during test load phases at the top of the pile T1.

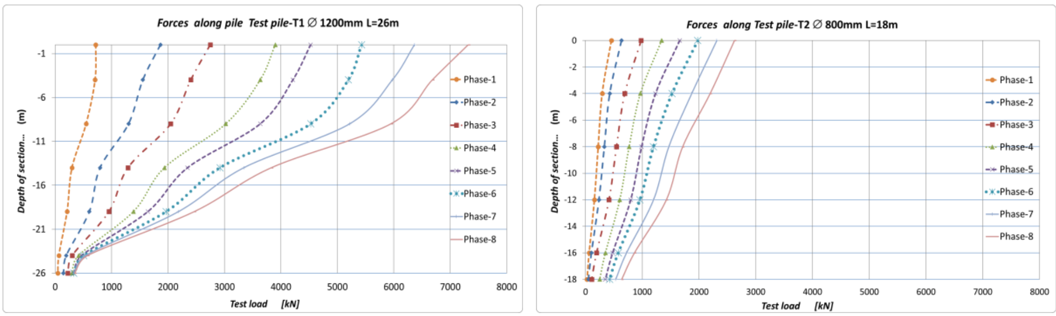

Figure 9. Force distributions along depth of tested piles T1 and T2

5. CONCLUSION

During static vertical load testing of piles, in addition to the inevitable measurement of settlement, strain measurement in several measuring sections along the depth of the pile is often used in order to assess parts of the load that are transmitted through the skin and base of shaft. Which part of the total load will be transferred to the ground in first or second way, depends on many factors, primarily on the soil in which the pile was made, construction technology, diameter and length of the pile, etc.

The representation of force transmission, according to the calculated values for the tested piles T1 and T2, over the base and shaft, with the total test loads during the test, illustrates the share of individual methods of force transmission to the ground, Figure 10.

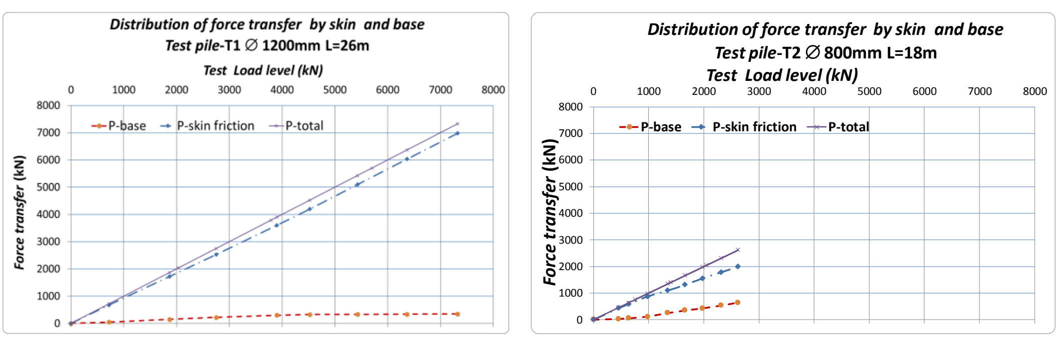

Figure 10. Force transfer by base and shaft during testing of piles T1 and T2

In general, it is evident that during the realization of significant settlements, there is a more significant mobilization of the surrounding soil, which results in higher shear stresses over the pile shaft. Of course, in layered soil, the way the load is transferred to the surrounding soil significantly depends on the characteristics of the soil layers and properties / stiffness of the soil where pile base is located.

A more detailed analysis, which would include elastic shortening of the pile in order to more accurately determine the realized shear stresses and the inclusion of the results of other tests (CPT etc.), would result in more accurate results, which should be included in future studies.

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LITERATURE

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