SAVEZ GRAĐEVINSKIH INŽENJERA SRBIJE

ASSOCIATION OF CIVIL ENGINEERS OF SERBIA

GEOTECHNICAL ASPECTS OF CIVIL ENGINEERING AND EARTHQUAKE ENGINEERING - Vrnjačka Banja, 01-03. novembar 2023.

Nikola Božović[1], Mladen Ćosić[2], Ksenija Đoković[3], Rajo Milićević[4], Marija Krstić[5]

PILE CAPACITY DISTRIBUTION ANALYSIS FOR SLT WITH REACTIVE SYSTEM

Summary: *In the paper, the analysis of the bearing capacity of the pile and the redistribution of the load on the pile toe and shaft was carried out. The tests were carried out by a static load test (SLT) incrementally increasing the compressive force on the test pile, and the tension force on the anchor piles. The test system consisted of one test pile and two anchor piles with a reaction beam. Two tests were conducted according to the same test program, where the test piles were of the same length, while the length of the anchor piles in the second test was increased. In the first test, the anchor pile failed, while in the second test, the test pile failed. Based on the achieved limit values of settlement of the test and anchor pile, the bearing capacity of the test pile at the toe and shaft was determined. Subsequently, a CPT test was carried out and the bearing capacity was calculated according to the LPC-CPT method.*
Keywords: *pile, shaft, toe, bearing capacity, testing, SLT*

ANALIZA RASPODELE NOSIVOSTI ŠIPOVA KOD SLT SA REAKTIVNIM SISTEMOM

Rezime:*U radu je prikazana analiza nosivosti šipova i preraspodela opterećenja na bazu i omotač šipova. Ispitivanja su sprovedena testom statičkog opterećenja (SLT) inkrementalno povećavajući silu pritiska na ispitnim šipovima, odnosno povećavajući silu zatezanja na ankernim šipovima. Jedan ispitni sistem čine jedan testni šip i dva anker šipa sa reakcionom gredom. Sprovedena su dva testa prema istom programu ispitivanja, pri čemu su testni šipovi bili iste dužine, dok je dužina ankernih šipova u drugom testu povećana. U prvom testu došlo je do otkaza ankernog šipa, dok je u drugom testu došlo do otkaza testnog šipa. Na osnovu ostvarenih graničnih vrednosti sleganja testnog i ankernog šipa utvrđena je nosivost testnog šipa po bazi i omotaču. Naknadno je sproveden CPT opit i izvršen proračun nosivosti prema LPC-CPT metodi.*
Ključne reči: *šip, omotač, baza, nosivost, ispitivanje, SLT*

[1] mast.inž.građ., Institut za ispitivanje materijala IMS, Beograd, nikola.bozovic@institutims.rs
[2] dr,dipl.inž.građ., Institut za ispitivanje materijala IMS, Beograd
[3] dr,dipl.inž.geol., Institut za ispitivanje materijala IMS, Beograd
[4] mast.inž.građ., Institut za ispitivanje materijala IMS, Beograd
[5] mast.inž.građ., Elixir Group, Novi Sad

1. INTRODUCTION

The design of structures founded on piles is carried out in several stages, of which the calculations and tests of the bearing capacity of the piles stand out. Calculations of the bearing capacity of piles are based on the application of:

- analytical and numerical methods for appropriate soil parameters obtained from laboratory tests,
- analytical methods from in-situ soil testing with different types of penetration tests,
- laboratory model tests of piles in interaction with the soil.

On the other hand, the most reliable results in determining the bearing capacity of piles are obtained by applying in-situ testing of piles with a static load test (SLT – Static Load Test) and a dynamic load test (DLT – Dynamic Load Test). In SLT, piles are tested up to geotechnical failure or even up to a certain load level when, after that, hyperbolic extrapolation methods are applied to estimate the ultimate bearing capacity. If the measurement of the stress distribution along the pile shaft is not provided, it is virtually impossible to reliably determine the percentage of the base and shaft in the total bearing capacity of the pile.

This paper presents the results of testing two piles for the construction of the Viaduct for high-speed railways Novi Sad - Subotica. The aim of the research is to determine the behavior of the piles and the distribution of the bearing capacity by the shaft and the base of the piles.

2. SLT PILE TESTING METHODOLOGY

The SLT test was conducted using a reactive system. In the first case, the test and anchor piles are the same length of 18m, while in the second case, the length of the anchor piles was increased to 30m, and the length of the test pile was kept at 18m. All piles are Ø120cm in diameter. The piles were driven at a relatively short distance, so it is considered that the geological conditions are almost identical for both piles. Testing of test piles SLT for vertical pressure force was performed by an experiment in which two hydraulic presses with individual capacity of 600t were used as a pressure device. The presses rest against a resisting structure made of a steel beam connected to two reaction piles by reinforcing bars (Figure 1). The reinforcement is welded on the upper side over the vertical plates and the system of plates and stiffeners, while on the lower side it is welded to the reinforcement anchored in the concrete of the reaction piles.

Figure 1. Reaction system consisting of a reaction beam anchored in two piles

Measurements of settlement of tested piles were carried out using four digital comparators that were connected to two reference beams at an angle of 90˚. The control system of measuring the test piles, the displacement of the anchor piles and the deformation of the reference system was carried out by geodetic observation with a Leica leveler. Two measuring points were positioned on the test pile, one on the anchor piles and one on the reference beams. The working force per pile was 5110kN, which was adopted as 100% of the test load. The tests were conducted in two cycles. In the first cycle, the load was applied in 4 increments of 25% of the working force until reaching 100% of the test load, and then the pile was unloaded to 0kN in two steps. In the second cycle, it is planned to apply the load in 8 increments of 25% of the working force until reaching 200% of the test load, which is 10220kN. The unloading of the pile to 0kN in the second cycle was carried out in 4 steps.

For the limit state of the load capacity of the pile, the criterion was adopted when the settlement of the pile reaches a value in the amount of 10% of the pile diameter.

3. RESULTS OF SLT PILE TESTING

In the first test, while maintaining a constant load value of 6388kN (125% of the test load) after 50 minutes, anchor pile A2 failed and its displacement recorded by the leveler was 280mm. The settlement of the test pile was progressive without reaching a flat plateau of deformation, i.e. without reaching the consolidation condition. Figures 2 and 3 and Table 1 show the results of the SLT of the first test.

F [kN]	U [mm] T-test pile	U [mm] Anchor - A1	U [mm] Anchor- A2
I cycle			
0	0	0	0
1278	0.63	-0.12	-0.32
2555	4.36	-0.35	-1.07
3833	15.99	-1.00	-3.49
5110	**34.62**	**-2.16**	**-11.20**
2555	32.88	/	/
0	28.98	-0.23	-4.71
II cycle			
1278	29.94	-0.48	-5.26
2555	31.38	-0.89	-6.51
3833	33.35	-1.46	-8.81
5110	40.17	-2.14	-12.99
6388	**66.10**	/	**-280.00**
0	58.49	/	/

Table 1. Results of the test 1

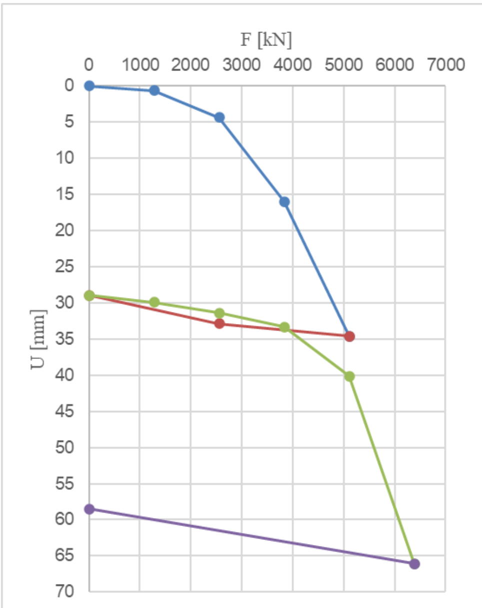


Figure 2. Load-settlement curve of the test 1

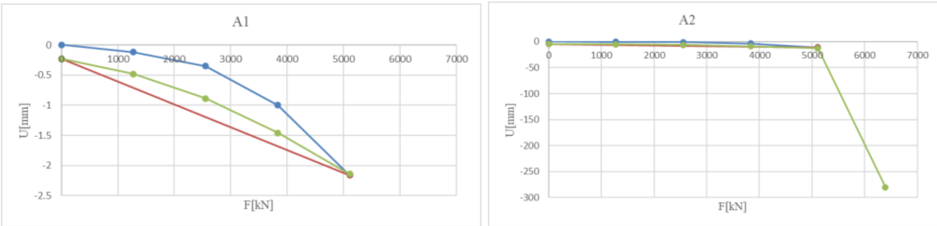


Figure 3. Load-displacement diagram for anchor piles - test 1

In the second test, the length of the anchor piles was increased, while the length of the test pile was kept the same as in the first case, and on that occasion the test pile reached the limit state for the axial compressive force. The measured displacement of the anchor piles was approximately uniform. In the second cycle, the test pile achieved a settlement of 120 mm when a force of 7665 kN (150% of the test load) was applied, which satisfied the failure criterion, so it can be stated that this force is also the limiting force for the pile. Figures 4 and 5 and Table 2 show the results of the SLT of the second test. The difference in settlement of the test piles in the first and second test amounts to a maximum of 20%.

F [kN]	U [mm] T-test pile	U [mm] Anchor-A1	U [mm] Anchor-A2
I cycle			
0	0	0	0
1278	0.85	-0.16	-0.16
2555	6.21	-0.52	-0.55
3833	14.86	-1.08	-1.24
5110	**30.35**	**-2.63**	**-3.18**
2555	28.78	/	/
0	26.06	-1.48	-1.03
II cycle			
1278	26.55	-1.59	-1.22
2555	27.73	-1.84	-1.78
3833	29.36	-2.21	-2.32
5110	38.07	-2.95	-3.14
6388	78.95	-8.7	-7.72
7665	**120.01**	**-22.79**	**-14.48**
0	110.64	-11.44	-6.48

Table 2. Results of the test 2

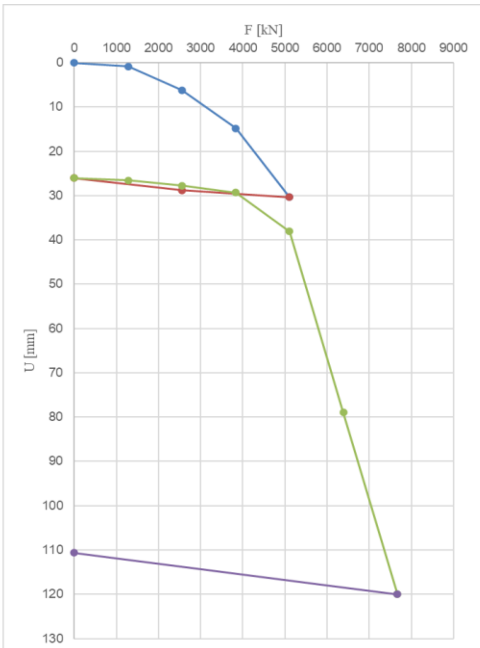


Figure 4. Load-settlement curve of the test 2

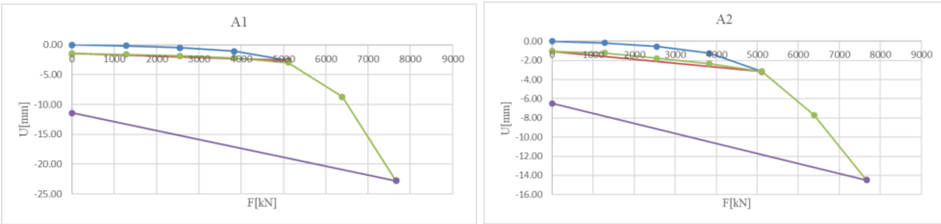


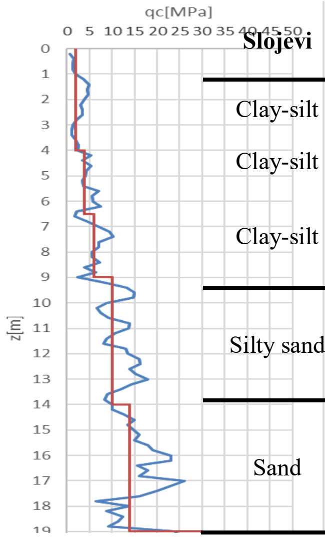
Figure 5. Load- displacement diagram for anchor piles - test 2

In the first test, the criterion of 10% was not met, when it is considered that the limit state of the pile under the action of the axial compressive force was reached, but a sufficiently large settlement of the pile was achieved for a force of 6388kN when the test was stopped. If there was enough reaction capacity to applied another increment, the test pile would very quickly enter the yield phase when the strains are constant for the same load level.

Since in the first test the limit state of the anchor pile was reached for the axial tensile force by an increment of 6388kN, we can adopt for the limit shaft load half of that amount, i.e. 3200kN. The total limit bearing capacity of the pile for axial compressive force was reached in the second test when the test was repeated with increased lengths of the anchor piles. A force of 7700kN is adopted for the total limit bearing capacity of the pile. Once we know the ultimate bearing capacity of the pile shaft based on the first test, the ultimate bearing capacity of the pile base would then be 4500kN. If we adopt values of 3 and 2 for the safety factor for the base and shaft, respectively, then the permissible bearing capacity for the base would be 1500kN, and 1600kN for the shaft, so the total permissible bearing capacity of the pile would be 3100kN. Based on the carried out load analysis and the test results shown, the settlement of the pile for the permissible load is 9mm, where the pile has already entered the non-linear behavior.

4. CALCULATION OF LOAD CAPACITY FROM THE RESULTS OF STATIC PENETRATION

After the first SLT test, a static penetration test (CPT - Cone Penetration Test) was conducted directly next to the test pile. Based on the obtained results, layer of soil types were defined, determined on the basis of Robertson's classification. Table 3 shows selected geological layers with parameters for the calculation of bearing capacity. The calculation of the permissible bearing capacity of the pile was carried out according to the LPC-CPT method with adopted safety factors for base 3 and casing 2. The limit bearing capacity of the pile is 7550kN, where the limit bearing capacity of the shaft is 4400kN, while the limit bearing capacity of the base is 3150kN. For the adopted safety factors, the permissible load capacity of the pile is 3250kN.



Slojevi	H [m]	q_c[MPa]	k_c	α/f_{lim}	f_{soil}
Clay-silt	4.00	2	0.4	0,65/90	55.23
Clay-silt	2.50	4	0.4	0,65/90	85.92
Clay-silt	2.50	6	0.4	0,65/90	101.75
Silty sand	5.00	10	0.2	0,65/90	117.15
Sand	5.00	14	0.2	1/90	104.08

Table 3. Geological layers with parameters for calculation of pile capacity

k_c - bearing capacity factor that depends on the type of pile and the type of soil
α - coefficient that depends on the type of pile and the type of soil
f_{lim} – shaft friction, which depends on the type of soil and the resistance of the cone
f_{soil} - the maximum value of shaft friction, which depends on the type of pile and soil

5. CONCLUSION

The paper presents a specific case from the practice of field tests of the bearing capacity of piles under the action of axial pressure force when the failure of the anchor and test pile occurred, which enabled the determination of the limit bearing capacity of the pile base and shaft. Since the test results did not meet the design criteria, a control CPT test was performed directly next to the tested pile. The obtained values of permissible forces from SLT and CPT tests are approximate and the difference is less than 7%.

Although the resistance of the cone in static penetration reaches significant values in the zone around the base of the pile, it is often the case that during testing the pile does not meet the design criteria. In practice, it turned out that this case is characteristic of saturated sands. That is why it is necessary to pay great attention to the pile construction technology in order to avoid all potential dangers that would lead to hydraulic fracture of the soil at the base of the pile and the creation of a mud zone that can significantly reduce the bearing capacity of the pile.

In the case when the designed bearing capacity of the pile is not met, the most common resolve way is to reduce the permitted bearing capacity for the designed pile geometry and increase the number of piles in the foundation. Another choice would be to strengthen the soil in the base by the injection process when there is no possibility to expand the foundation footing. The geological conditions in which the piles are constructed, the pile construction technology and the pile geometry are factors that affect the axial bearing capacity of the pile and the load distribution from the pile to the soil.

Acknowledgments

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Reg. No. 451-03-47/2023-02 /200012.

6. REFERENCES

[1] Izveštaji Instituta IMS br. 43-2589 od 09.03.2023. i br. 43-6480 od 06.06.2023.
[2] El-Reedy M.: Geotechnical data and pile design (Chapter 004), Gulf Professional Publishing (2012)
[3] EN 1997-1:2004, Geotechnical Design - Part 1: General Rules, European Committee for Standardisation, Brussels, Belgium, (2004)
[4] Fellenius B.: Discussion of Bohn C., Lopes dos Santos A., Frank R.: Development of axial pile load transfer curves based on instrumented load tests, Journal of Geotechnical and Geoenvironmental Engineering 144(4) (2018). https://ascelibrary.org/doi/10.1061/%28ASCE%29GT.1943-5606.0001867
[5] Nanda S., Patra N.: Theoretical load-transfer curves along piles considering soil nonlinearity, Journal of Geotechnical and Geoenvironmental Engineering 140(1) (2014) 91–101. https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29GT.1943-5606.0000997
[6] Żarkiewicz K.: Pile bearing analysis based upon ultimate values of toe and skin resistance as well as their mobilization with settlement, MATEC Web Conference, 29th International Conference on Structural Failures, (2019) https://doi.org/10.1051/matecconf/201928403011