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Experience in execution of driven reinforced concrete piles in Croatia

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Subject review

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The technology of driven, precast reinforced concrete piles is increasingly being used on the domestic market. The advantage of this technology lies in soil displacement during installation, which enhances the pile's bearing capacity. The production process ensures reliable material quality and pile integrity. The bearing capacity of piles can be quite accurately assessed using modern calculation methods and standard soil investigation procedures, including high quality laboratory and field testing. Dynamic testing methods enable a relatively quick and cost-effective verification of the bearing capacity of installed piles. The paper presents experiences with the application of this technology in Croatia, including details on soil geotechnical profiles, driving technology, quality control, and achieved pile load-bearing capacities under specific soil conditions.

Key words:
driven piles, soil investigation, dynamic pile testing

Pregledni rad

Igor Sokolić, Boris Kereš

Iskustva u primjeni zabijenih AB pilota u Hrvatskoj

Na hrvatskom tržištu sve češće primjenjuje se tehnologija zabijenih, predgotovljenih armiranobetonskih pilota. Prednost je ove tehnologije razmicanje tla prilikom ugradnje, što doprinosi nosivosti pilota. Proces proizvodnje osigurava pouzdanu kvalitetu materijala i integritet pilota. Moguća je vrlo pouzdana procjena nosivosti pilota na temelju suvremenih metoda proračuna i standardnih istražnih radova, koji uključuju kvalitetna laboratorijska i terenska ispitivanja. Metoda dinamičkog ispitivanja omogućava relativno brzu i povoljnu provjeru nosivosti izvedenih pilota. U radu su prikazana iskustva u primjeni ove tehnologije u Hrvatskoj, uključujući detalje o geotehničkom profilu tla, tehnologiji zabijanja, kontroli kvalitete i postignutoj nosivosti pilota u karakterističnim uvjetima u tlu.

Ključne riječi:
zabijeni piloti, ispitivanje tla, dinamičko ispitivanje nosivosti pilota

1. Introduction

Recently, the technology of driven, precast reinforced concrete piles is increasingly being used on the Croatian market. Driven piles are a type of pile that is characterized by the fact that during implementation, the soil is displaced during driving (there is no excavation of material by drilling), which ensures increased lateral pressures and increased load-bearing capacity through friction over the shell compared to bored piles [1]. Additionally, compared to drilling technologies, reliable integrity of the final structural element is ensured. Precast reinforced concrete elements, which are produced under controlled conditions in production plants and delivered ready-made to the installation location, are used. A great advantage of driven pile technology is the quality control of installation. More precisely, when driving each pile, a driving protocol is followed - the required number of blows of a weight of known mass, dropped from a known height, to achieve a certain penetration of the pile. Based on the recorded number of blows, the load-bearing capacity of each installed pile can be indirectly estimated. The load-bearing capacity of piles can be measured relatively inexpensively by dynamic testing. The procedure is carried out at various depths during pile driving, immediately after the driving is completed, and after the surrounding soil relaxes and pore pressures dissipate when the pile reaches its final load-bearing capacity. In addition to the above advantages of driven pile technology, it is necessary to highlight its disadvantages compared to bored piles, which primarily relate to the possibility of installation and adaptation to the actual soil conditions: the potential risk of driving the piles to the designed depth if the materials on site are harder than expected, and the technologically more demanding extension of the pile on site if it proves necessary during implementation.

This paper presents experiences in the application of driven reinforced concrete piles on several examples in Croatia: the Zeleni brijeg sports hall in Sisak (HALL), the Đakovo wastewater treatment plant (UPOV), the transshipment station in Karlovac (TRANSSHIPMENT STATION) and the Plodine supermarket in Lepoglava (PLODINE). For each location, a complete overview of the geotechnical soil profile, characteristic driving protocols, and measured pile load-bearing capacities are provided (a total of 24 dynamic pile tests). An analysis of the driving protocol was conducted and a comparison of the calculated load-bearing capacity and the load-bearing capacity measured by dynamic testing was provided. The pile load-bearing capacity was assessed using modern calculation methods, i.e., primarily using CPTU tests and recommendations according to Bustamante & Gianeselli [2] (the procedure is described in detail in Lune et al. [3]) and based on other in-situ and laboratory tests (SPT, DPH, uniaxial strength) using the alpha-beta method according to API [4].

It should be noted that according to Eurocode 7, dynamic testing may be used to assess the compressive load-bearing capacity of piles, provided that an appropriate site investigation and calibration of the method have been carried out using a static load testing of the same type of pile, of similar length and cross-section, and under comparable conditions in the foundation soil. Despite the fact that static tests were not available for the projects analyzed in this paper, the results of dynamic tests were presented and analyzed as valuable data for assessing the load-bearing capacity of piles.

2. Technology of implementation of driven reinforced concrete piles

The process of implementing driven reinforced concrete piles is carried out in accordance with the requirements of the HRN EN 12699:2015 standard [5]. Precast piles are delivered to the construction site. Using driving machines, the piles are lifted into a vertical position and positioned at the installation site. This is followed by driving the piles using a diesel hammer or hydraulic hammer. During the driving of piles, the verticality of the piles is controlled in two vertical directions. By taking into account the soil conditions, the driving procedure is adjusted by gradually increasing the height from which the driving weight is dropped. With a hydraulic hammer, the height of the weight drop can be manually controlled, while with a diesel hammer, the height is the result of ground resistance with each stroke of the hydraulic piston. Driving is carried out to the final depth, with the final height of the pile head being geodetically controlled. When installing piles, a driving protocol is recorded, which contains data by depth on the required number of hammer blows for a certain penetration of the pile (in the paper, the number of blows used is N_{25} for a pile penetration of 25 cm). After installing the pile, if necessary, the pile head is prepared by removing excess concrete or by crushing it with hydraulic pliers. The procedure of implementing driven RC piles is shown schematically in Figure 1.

The driving of all piles analyzed in this paper was carried out by the company Monterra d. o. o. [6] using a diesel hammer type DELMAG 25-32 [7], whose weight weighted 2.5 tons (used in the HALL project) and a hydraulic hammer type JUNTAN HHK5 A [8], whose weight weighted 5.0 tons (used in the UPOV, TRANSSHIPMENT STATION and PLODINE projects).

Figure 1. Technology of implementation of driven piles (lifting, positioning, driving, preparing the pile head with pliers)


Figure 2. Precast RC piles (design, pile top – steel spike, pile head)

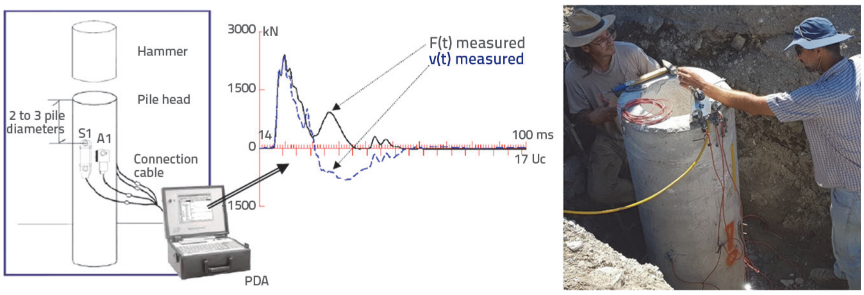


Figure 3. Dynamic pile load-bearing capacity testing: schematic representation of the PDA procedure and a photo of sensor installation

Precast reinforced concrete piles were manufactured at the concrete pile factory TBS d. o. o. [9]. The piles are 50 and 60 cm in diameter, made of C40/50 strength concrete, reinforced with B500B quality steel. They are manufactured using a centrifugal process, which ensures ideal geometry, homogeneity and integrity of each pile. During the manufacturing process, a steel spike is installed at the top of the pile, and if necessary, a steel connector for connecting piles longer than 13 m. The pile itself is of hollow cross-section with a wall thickness of 10 to 12 cm (Figure 2).

The load-bearing capacity of driven piles can be tested by static and/or dynamic field testing. Given the speed of implementation and the possibility of relatively inexpensive testing of a larger number of piles, dynamic testing using the Pile Driving Analyzer (PDA) procedure [10] is often used in practice, in accordance with the standard ASTM D4945-17 [11]. The procedure involves installing measuring equipment on the pile head, consisting of an accelerometer for measuring pile acceleration and a strain gauge. Two sensors of each type are placed in pairs at a distance of 2 to 3 diameters below the pilot's head. The sensors are connected to a PDA receiver in which signal collection and processing are performed and the output measurement results are displayed simultaneously with the pile driving. For each blow, the impact force $F(t)_{measured}$ and the pile penetration speed $v(t)_{measured}$ are calculated as a function of time. The PDA procedure is schematically shown in Figure 3. The measured data are analyzed in the CAPWAP computer program [12], which is based on the theory of shock wave propagation through a pile supported by a series of elastoplastic springs along the shell and at the pile base. The soil and pile model are simulated in the program by the measured record of pile head displacement $v(t)_{measured}$. The result of the calculation is the pile reaction in the form of the realized force at the pile top $F(t)_{modeled}$. Back analysis is required to calibrate the model parameters to achieve maximum overlap with the measured $F(t)_{measured}$ and calculated $F(t)_{modeled}$ value. Based on the calibrated model data, it is possible to estimate the maximum activated load-bearing capacity of the pile shell and base. It is also possible to model the static load on piles and predict the working load-bearing capacity diagram of piles. The procedure is carried out during the implementation of the piles at the selected depths and at the final driving depth. Additional tests at the final depth are performed at a time delay (typically after 6 days and 24 days) in order to assess the increase in pile load-bearing capacity due to soil consolidation. Dynamic load-bearing capacity tests of all piles presented in this paper were conducted by the independent testing company Geotest d. o. o. [13], according to an accredited test method in accordance with the requirements of the ISO 17025:2017 standard.

3. Projects with driven RC piles

3.1. Zeleni Brijeg Sports Hall, Sisak (HALL)

The Zeleni Brijeg Hall in Sisak has floor plan dimensions of approximately 60 x 70 m. It was constructed as a reinforced concrete structure, a combination of monolithic and precast elements (Figure 4).


Figure 4. Zeleni Brijeg Hall in Sisak during construction

The main roof beam with a span of 45 m is supported by reinforced concrete cores which are approximately 13 m high. The foundation of the building was constructed on strip foundations around the perimeter of the building and on a reinforced concrete slab under the core and stands, under which driven RC piles were installed. The diameter of the piles is 60 cm, their length is 8.5 to 10.5 m, and they are embedded in the bearing layer of sand (Figure 5).

As part of the geotechnical investigation works, 6 exploration boreholes were drilled, 4 probes were implemented using dynamic penetration (DPH), and 3 probes were implemented

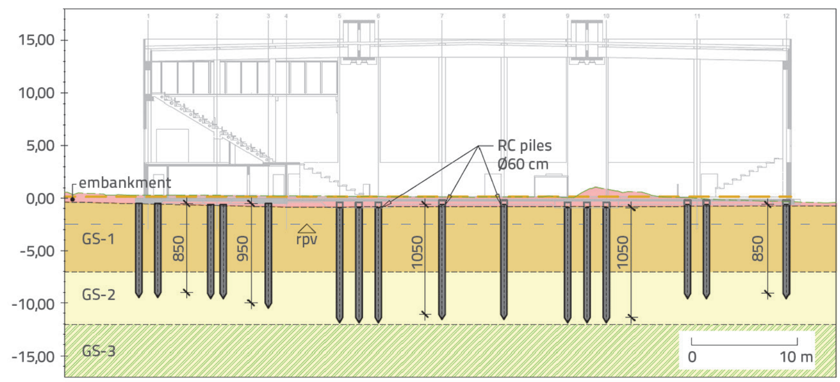


Figure 5. Characteristic cross-section of the hall and soil profile

According to static calculations, the characteristic load-bearing capacity of a pile for permanent conditions is, depending on the length of the pile: 1455 kN (L = 9 m), 1587 kN (L = 10 m) and 1719 kN (L = 11 m). The load-bearing capacity of the pile over the base is about 70 %, while over the shell it is 30 % (the pile with load-bearing capacity dominantly at the top). Dynamic testing of pile load-bearing capacity measured the following values: 2084 kN (L = 9 m), 2346 kN (L = 10 m) and 2323 kN (L = 11 m). Measurement of the pile load-bearing capacity after 7 days indicates a minimal increase by only 4 % (2323 kN → 2415 kN), which is characteristic of piles in incoherent materials (sand). Number of blows during pile driving for a pile penetration length of 25 cm (N_{25}) is less than 10 blows in layer GS1, gradually increases in layer GS2 to about 50 blows and reaches a maximum value of up to 125 blows in layer GS3 (Figure 6).

using static penetration with pore pressure measurement (CPTU). During the exploratory drilling, a standard penetration test (SPT) as well as laboratory tests were conducted to determine the mechanical and physical characteristics of the soil (soil classification, Atterberg plasticity limits, granulometric composition, direct shear, oedometer). The geotechnical soil profile consists of four characteristic geotechnical areas (Figure 6): N – sand and gravel filling (up to a depth of about 2.0 m); GS1 – low-plastic clay of medium to difficult-to-knead consistency, with poor mechanical characteristics up to a depth of about 7.0 m; GS2 – clayey, poorly graded sand, medium compaction (up to a depth of about 9.0 m) or compacted (up to a depth of 12 m) and GS3 – very compacted sand/gravel (up to the depth of the testing, 16 m).

3.2. Wastewater treatment plant, Đakovo (UPOV)

The Đakovo wastewater treatment plant (UPOV) was built in the southeastern part of the city of Đakovo, along the Ribnjak canal. The plant consists of several characteristic buildings: an administration building, a processing plant and biological basins,

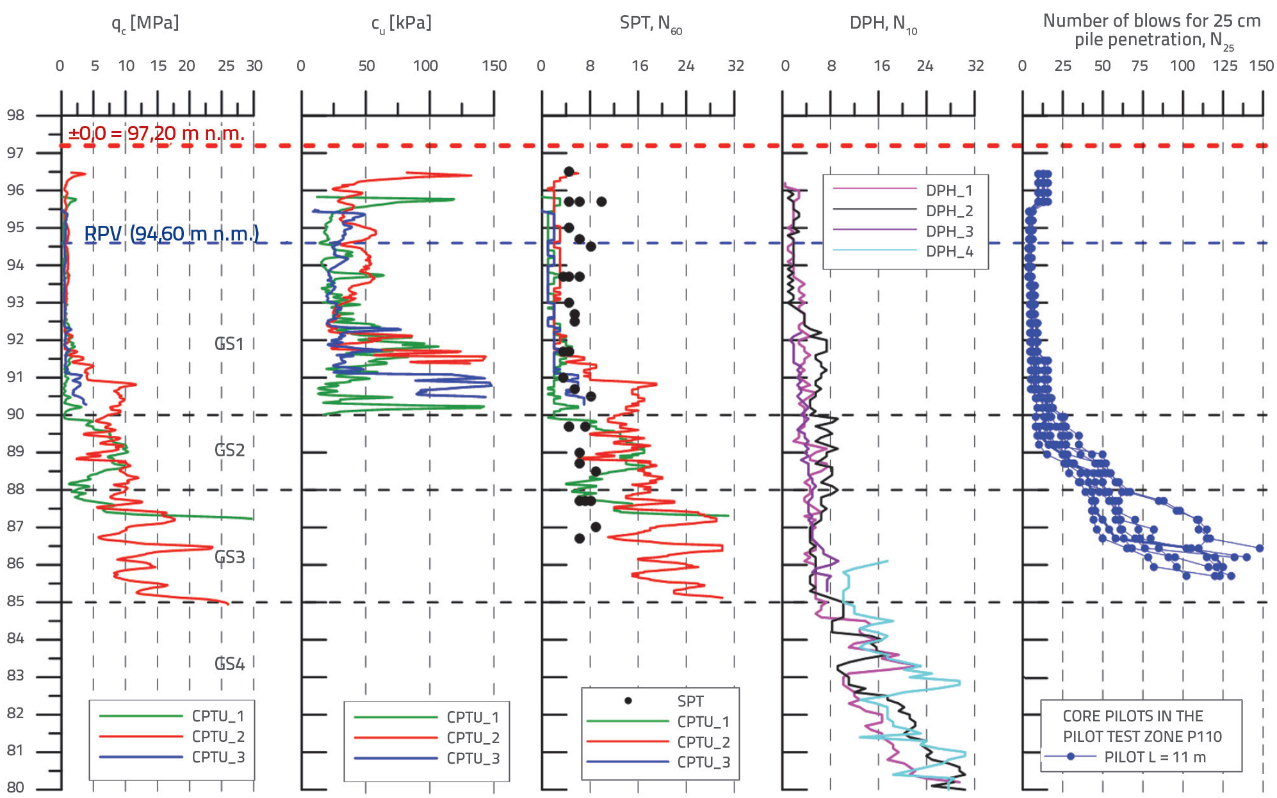


Figure 6. Geotechnical soil profile (results of on-site testing: CPTU, SPT, DPH) and records of pilot driving

and a solar sludge drying plant (Figure 7). A critical facility from a foundation perspective is a biological basin measuring approximately 70 x 80 m, 6.6 m high, of which approximately 3.0 m is constructed below the level of the future filling, i.e., approximately 2.0 m below the level of the existing terrain. In the above circumstances, the effect on the foundation soil beneath the basin is around 80 kPa in the case of a full basin, and buoyancy is also possible in the case of a high groundwater level at the time of emptying or servicing the basin, i.e., down to -30 kPa. Given the unfavorable soil conditions (soft clay and powders), the facility is founded deep on driven piles with a diameter of 50 cm, and a length of 10 and 12 m. Figure 7 shows the pile construction with the quality control during pile driving (geodetic control of the position in the x, y, z directions and control of the pile verticality with a level indicator).

Figure 7. Đakovo WWTP (UPOV) during construction

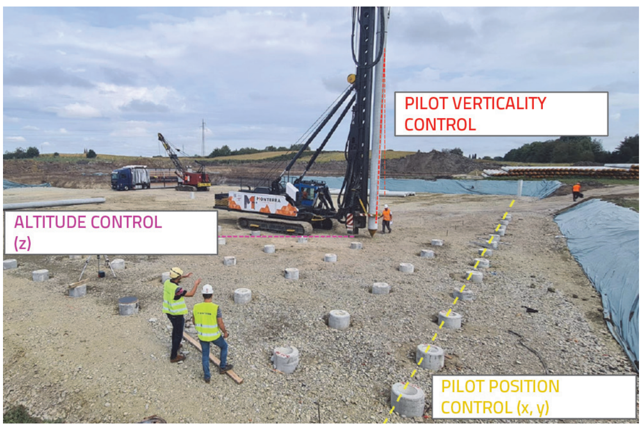


Figure 8. Installation of piles with specified performance control in accordance with the requirements of the HRN EN 12699:2015 standard (maximum position deviation <0.1 m and inclination angle <0.04 m/m)

Geotechnical investigation consisted of previous investigations in the preliminary design phase (1 exploration borehole, 3 x CPTU to a depth of 8 m) and investigations for the main project (3 boreholes, 4 x CPTU to maximum injection depth, piezometer with electrical reading of the groundwater level – DIVER). The geotechnical soil profile consists of the surface layer of the filling with poor mechanical characteristics (CI/CH clays and MH powders, very soft to soft consistency), GS1 – clays and powders of medium to solid consistency, GS2 – powders (depths up to about 5 m), clayey with a higher content of sand (at depths > 12 m) and GS3 – clayey sand (at depths > 14.5 m). The groundwater level was recorded at a depth of 0.6 to 2.4 m below ground level with an estimated rise during the wet period of the year. During the works, a rise in the groundwater level, practically to the surface of the terrain, was recorded in the piezometer.

The characteristic calculated value of the pile load-bearing capacity is, depending on the pile length, 572 kN (L = 8 m), 682 kN (L = 10 m) and 1013 kN (L = 12 m). The piles are the so-called floating piles, with about 80 % of the load-bearing capacity being realized through the shell and 20 % through the base.

During the pile implementation phase, dynamic testing was conducted on 4 test piles. A PDA analysis was performed on the first pile for three characteristic pile depths (8 m, 10 m and 11.1 m) and subsequent testing was performed 6 days after installation. The values obtained for the load-bearing capacity of the 11.1 m long pile during installation were 1092, 947, 1152 and 1326 kN, while the increase in load-bearing capacity after 6 days was approximately 25 % (1092 kN → 1342 kN). Given that the pile load-bearing capacity (R_{test} = 947 kN) that was measured on pile B-254 was approximately equal to the calculated value (R_{cal} = 954 kN) and achieved as a result of driving according to the protocol for $N_{25,\ average}$ = 14, the specified value was chosen as relevant for the assessment of load-bearing capacity: *The load-bearing capacity of the pile is ensured provided that in the last three driving intervals a minimum of 14 blows are achieved for a penetration of 25 cm, under a weight weighing 5 tons, which is dropped from a height of 55 cm.* In doing so, an additional reserve in load-bearing capacity resulting from the additional driving of piles in a length of 50 cm after testing (increase in load-bearing capacity compared to the test result) was retained, as well as the additional effect of increasing load-bearing capacity due to soil consolidation (approximately 25 %). Figure 9 shows the geotechnical soil profile (CPTU test results) and a record of pile driving and associated driving energy.

Based on the driving protocol of all implemented piles, a load-bearing capacity analysis was conducted in relation to the given criteria. An overview of the average number of blows for the last three pile installation intervals ($N_{25,\ average}$) is given in Figure 10. It clearly shows zones of softer and more compacted foundation soil in the basin zone. Statistical analysis of the results yielded a log-normal distribution of $N_{25,\ average}$ value, where the mean value of the measured results is $N_{25,\ average}$ = 15.5 blows, which is greater than the given criterion $N_{25,\ average}$ >14 (Figure 11). If the increase in load-bearing capacity of piles by 25 % due to consolidation is taken into account, it can be assumed that piles that have a lower number of blows at the end of driving $N_{25,\ average}$ > 11 also satisfy the load-bearing capacity for the permanent state after consolidation (14/1.25 = 11.2). Given that 95 % of the piles meet the driving criterion $N_{25,\ average}$ > 11 blows, it can be concluded that the load-bearing capacity of all piles is ensured

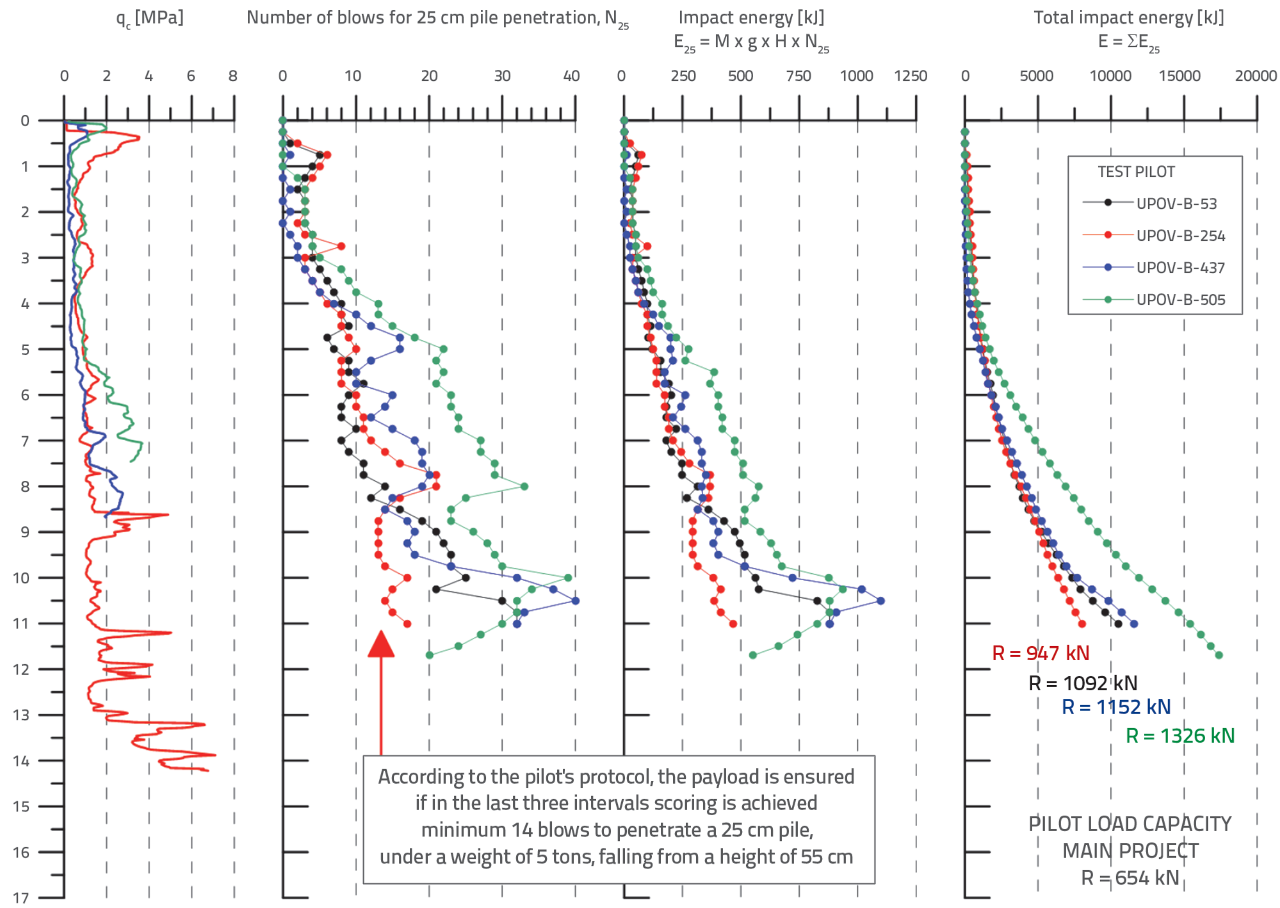


Figure 9. Geotechnical soil profile (CPTU test results) and pile driving record and associated energy (UPOV)

for the permanent state in accordance with the requirements of Eurocode 7 for geotechnical design. The additional reserve in load-bearing capacity results from the additional 50 cm of driving after testing and from the robustness of the foundation system, which allows for load redistribution to adjacent piles in the group in the event of a difference in load-bearing capacity.

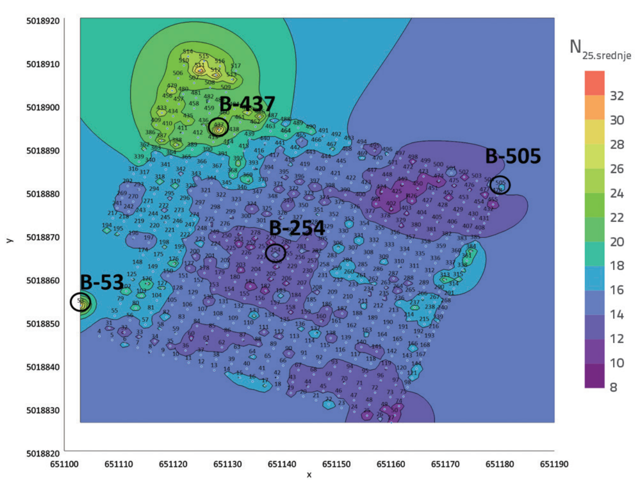
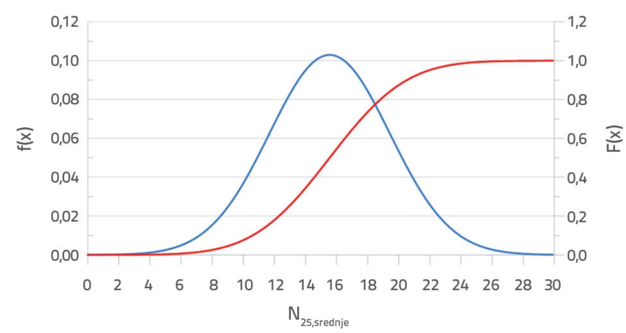


Figure 10. Overview of the average number of blows for the last three intervals of installation of piles per 25 cm, $N_{25,\ average}$



		$N_{25,srednje}$	R^1 [kN]	R^6 [kN]
Srednja vrijednost		15,6	946	1154
Standardna devijacija		3,9	39	47
Fraktile [%]	**5**	10,7	897	1094
	10	11,3	903	1102
	25	13,0	920	1122
	50	15,0	940	1147
	75	17,0	960	1171
	95	22,8	1018	1242

Figure 11. Statistical processing of pile driving data: cumulative distribution function f(x) and probability density function F(x) (diagram above). Measured values of the number of blows for the last three intervals ($N_{25,\ average}$), correlated pile bearing capacity immediately after driving (R^1) and estimated pile bearing capacity 6 days after driving (R^6) (table below)

3.3. Transshipment station, Karlovac

The transshipment station is a steel structure for the transshipment of waste material. It is based on a reinforced concrete grillage that rests on driven reinforced concrete piles. Driven RC piles with a diameter of 60 cm and lengths of 16 and 18.5 m were selected. A characteristic cross-section of the structure, foundation and foundation soil is shown in Figure 12.

The geotechnical soil profile consists of: FILLING – heterogeneous bulk material from municipal and construction waste (depth up to about 5.5 m), GS1 – layer of incoherent sand, lightly to medium compacted (thickness 2 to 4 m), GS2 – layer of clay with sand of low plasticity, very soft to soft consistency (thickness of about 3 m), GS3 – layer of powdery sand of medium compaction (thickness of about 1.5 m), GS4 – layer of clay of medium to high plasticity, medium consistency (thickness of about 15 m). The groundwater level was recorded during drilling at a depth of 1.1 to 1.6 m.

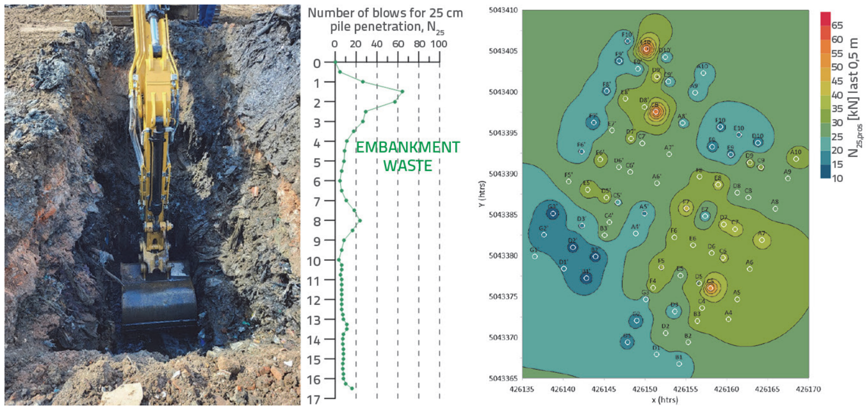


Figure 13. Excavation of a test pit in the filling zone, pile driving diagram and overview of the average number of blows for the last two pile installation intervals of 25 cm, $N_{25,\ average}$ (TRANSSHIPMENT STATION)

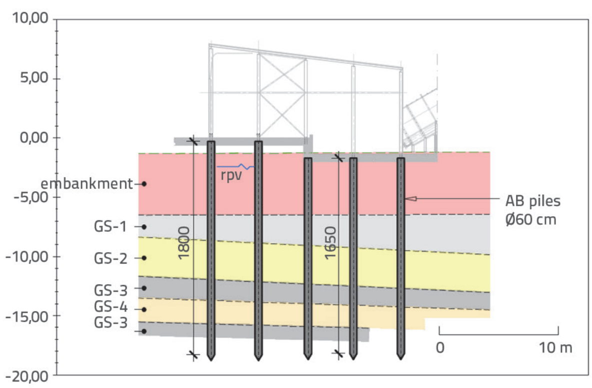


Figure 12. Characteristic cross-section of the structure and piles, and geotechnical soil profile (TRANSSHIPMENT STATION)

The pile load-bearing capacity was calculated based on in-situ (SPT) and laboratory tests using the API method. The piles are the so-called floating piles, with a characteristic load-bearing capacity of 879 kN, with 80 % of the load-bearing capacity relating to the shell and 20 % to the base. Dynamic testing measured the load-bearing capacities of piles after driving them in four positions: 1870, 876, 936 and 954 kN, with an increase in load-bearing capacity by 16 % (1870 kN → 2737 kN) 6 days after pile driving. There is an evident dispersion in the obtained test results, which results from the heterogeneity of the foundation soil, different conditions in the pile base zone, and above all, the heterogeneity of the filling material. The dispersion of results is also visible in the graphic representation of the average number of blows for the last two intervals of driving piles $N_{25,average}$ (Figure 13). Based on the pile driving records, a high penetration resistance can be observed in the filling zone, which can potentially affect the load-bearing capacity of the shell in that layer. Given the nature of the waste material (degradation over time), this contribution to the load-bearing capacity was disregarded in the calculation (engineering assessment on the safety side). The number of blows in the foundation soil under the filling is relatively small (N_{25} = about 10 to 20 blows).

3.4. Plodine Supermarket, Lepoglava

The Plodine supermarket building in Lepoglava is a reinforced concrete frame structure based on piles. At the top of the pile is a cap into which the columns are mounted. The caps are connected by reinforced concrete joists. Driven RC piles with a diameter of 60 cm and a length of 11 m were selected (Figure 14). Given the occurrence of solid materials in the substrate at a depth of about 8 m and the capacity of the driving equipment, some piles were driven to a shallower depth (about 10 m).

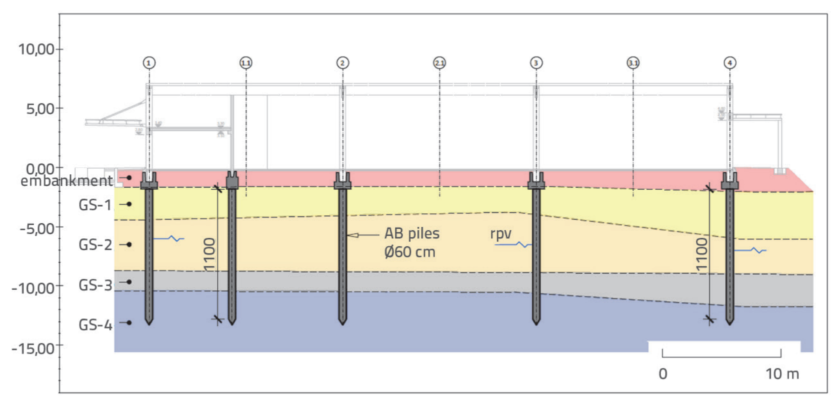


Figure 14. Characteristic cross-section of the structure and piles, and geotechnical soil profile (PLODINE)

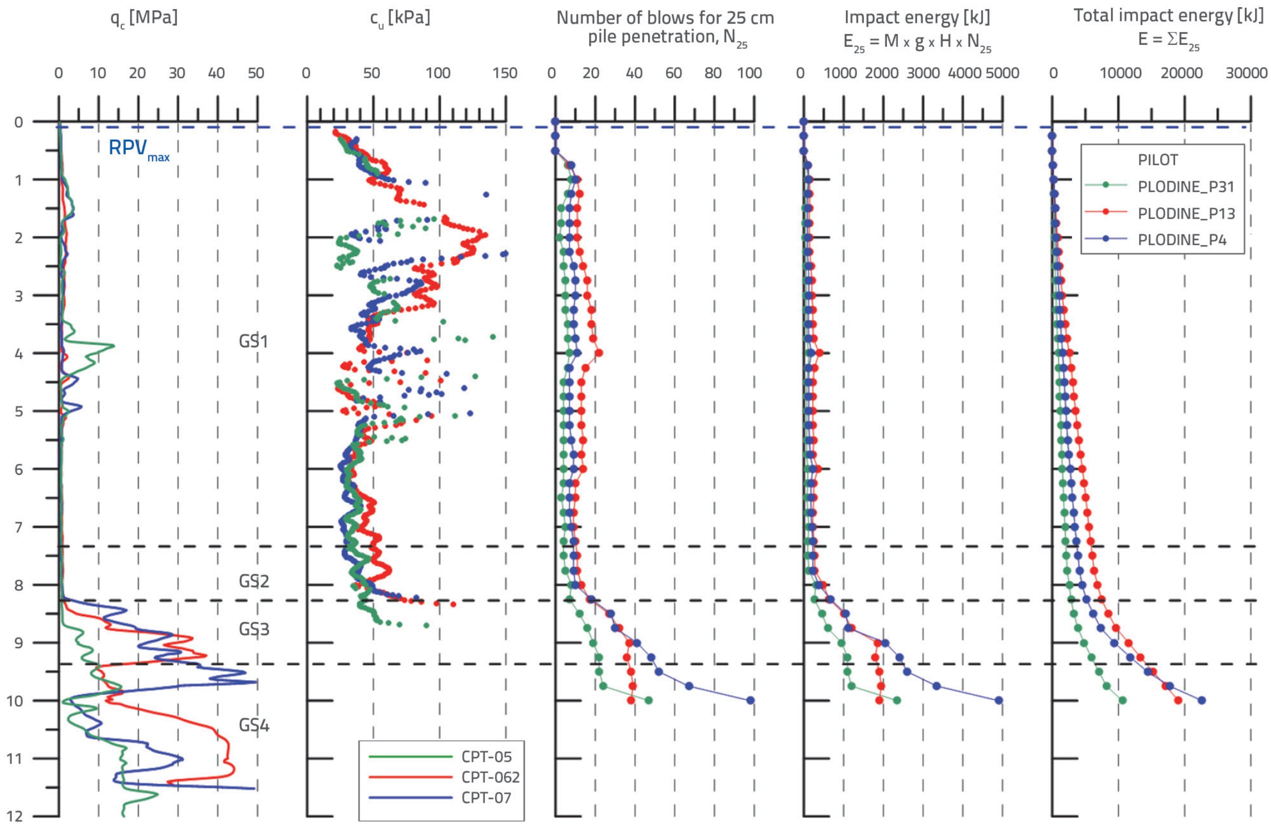


Figure 15. Geotechnical soil profile (results of on-site testing: CPTU) and pile driving record (PLODINE)

Geotechnical investigation consisted of field investigation (7 x CPTU, 2 x DPH) and one control exploration borehole during the construction phase with a depth of 15 m. The geotechnical soil profile consists of: FILLING – made of crushed stone material, which is up to 75 cm thick, GS1 – clays and powders of medium plasticity, medium to soft consistency (up to a depth of about 7.3 m), GS2 – poorly graded, powdery sands, lightly to medium compacted (up to a depth of about 8.0 m), GS3 – sandy/powdery gravels, very compacted (up to a depth of about 9.3 m), GS4 – powdery weathered marl, solid consistency (up to a testing depth of 15 m).

The characteristic load-bearing capacity of piles determined by CPTU testing for a pile installation depth of 10 m is 1700 to 2500 kN, of which the load-bearing capacity per shell is approximately 500 to 650 kN (or approximately 25 % of the total load-bearing capacity). The majority of the load-bearing capacity is achieved through the pile base, around 75 % (the pile that is load bearing on the top). Figure 15 shows a characteristic CPTU test result and pile driving protocol. The number of blows for a penetration of 25 cm is about N_{25} = 10 in soft layers until the bearing layer appears. In the gravel layer, the number of blows increases rapidly to the final value of the driving in the marl layer of N_{25} > 80.

4. Analysis of the results

The research results are presented graphically on characteristic diagrams relevant for the assessment of mechanical characteristics of soil (results of in-situ CPTU and SPT tests), with pile driving protocols shown (number of blows during installation of pile N_{25}), corresponding to the total energies required for driving the piles and the load-bearing capacities measured by the dynamic test. It is evident that for all piles the total driving energy increases approximately linearly with depth, i.e., until the appearance of harder materials in the substrate, after which the total energy gradually increases. In the case of piles which are load-bearing at the top, the energy consumption increases sharply (TRANSSHIPMENT STATION – foundation in marl, HALL – foundation in compacted sand), after which a large number of hammer blows N_{25} > 70 are required for each further displacement of the pile at maximum equipment capacity (about 40 to 60 kJ). In general, it can be concluded that the load-bearing capacity of floating piles for a theoretical driving energy consumption of about 10,000 kJ is greater than 900 kN, and for piles that are load-bearing on top, the theoretical driving energy consumption of about 20,000 kJ is greater than 2000 kN. The stated load-bearing capacity of floating piles is achieved with a relatively small number of blows at the end of driving 15 < N_{25} < 20 (pile penetration during testing with > 10 mm), and at the end of driving piles with load-bearing capacity on top, significantly higher numbers of blows N_{25} > 70 occur at the maximum capacity of the driving equipment (pile penetration during testing with < 4 mm). It should be noted that the measured load-bearing capacities in conditions of piles with load-bearing capacity on top are up to 2700 kN (in sand), and are estimated to be significantly higher in marl (calculated load-bearing capacity > 4000 kN).

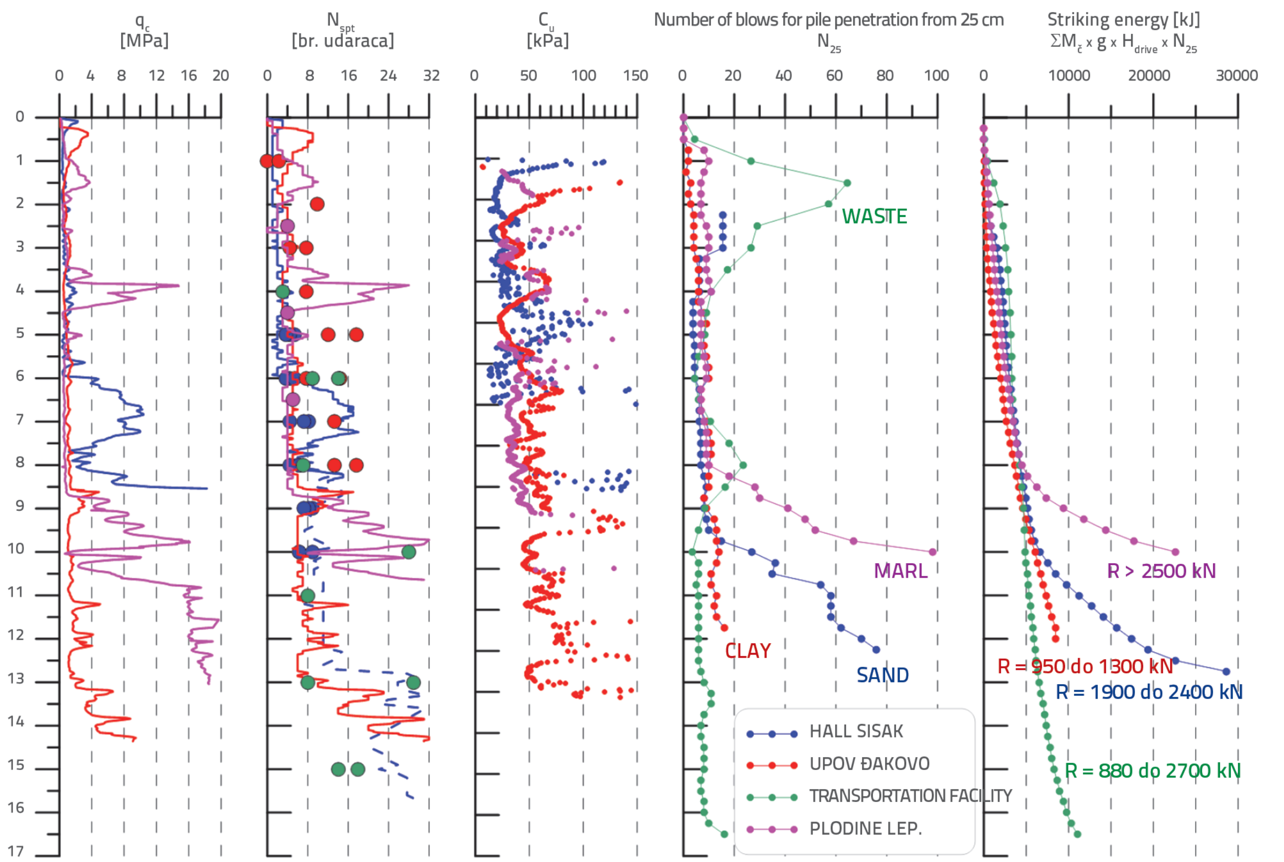


Figure 16. Comparison of results for all analyzed locations: investigation works (CPT, SPT, c_u), pile driving record (N_{25}) and the total energy required for pile driving

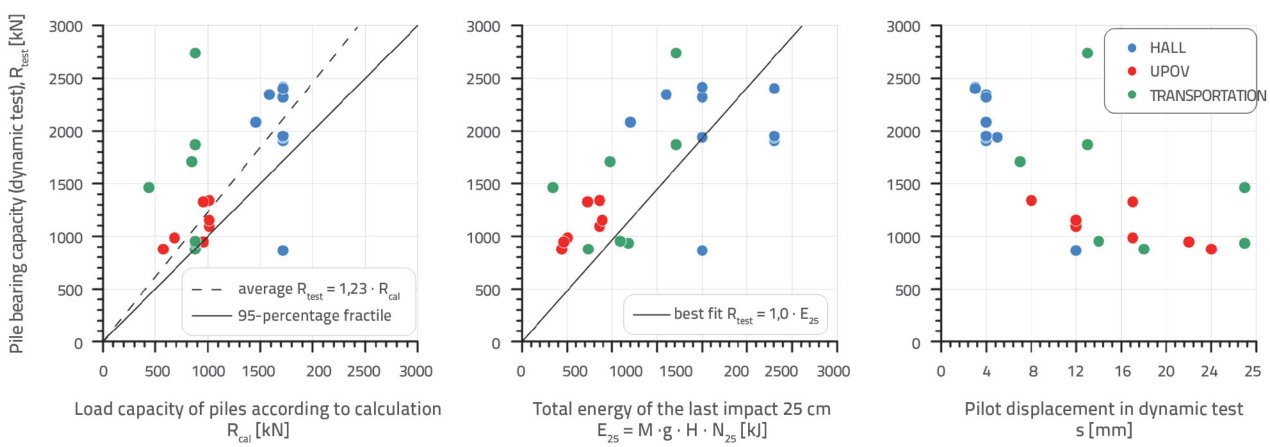


Figure 17. Analysis of pile test results: comparison of the tested load-bearing capacity of piles (R_{test}) in relation to the calculated value (R_{cal}); the impact of pile driving energy for the last 25 cm (E_{25}) on the pile load-bearing capacity (R_{test}); pile displacement due to dynamic testing (s) and associated load-bearing capacity (R_{test})

Detailed data on the driving protocol and dynamic testing are given in Table 1. A total of 24 dynamic tests of piles were carried out, in which the driving energy (E_{test}), settlement after testing (s) were calculated, while the pile load-bearing capacity (R_{test}) was estimated using back analysis. For each testing depth (L), data on the test pile driving protocol is given: hammer mass (M_h), drop height during driving (H_{drive}), the corresponding theoretical driving energy ($E_{t,drive}$), the number of blows required for pile penetration of 25 cm (N_{25}) and the corresponding energy required to drive a pile in the length of 25 cm immediately before testing ($E_{t,drive} = M_h x g x H_{drive} x N_{25}$, where g - acceleration of gravity is 9.81 m/s^2). On the basis of the energy measured during testing and the penetration of the pile, the corresponding energy required for the penetration of 25 cm was extrapolated ($E_{25,test} = E_{test}$ x 250 mm/s).

Table 1. Data on the tested piles (geometry and driving procedure, results of static calculation and dynamic pile load-bearing capacity testing, analysis of driving energy and penetration depth due to driving)

PROJEKT	PILOT	L	$M_č$	H_{drive}	$E_{t,drive}$	N_{25}	H_{test}	$E_{t,test}$	E_{test}	s	R_{test}	R_{cal}	R_{test}/R_{cal}	$E_{25,t}$	$E_{25,test}$
		[m]	[t]	[cm]	[kJ]	[udarci]	[cm]	[kJ]	[kNm]	[mm]	[kN]	[kN]	[ ]	[kJ]	[kJ]
DVORANA	P85-Test 1	9	2,5	-	40	>30	-	40-60	38,5	4	2.084	1.455	1,43	1.200	2.406
DVORANA	P85-Test 2	10	2,5	-	40	>40	-	40-60	37,4	4	2.346	1.587	1,48	1.600	2.338
DVORANA	P85-Test 3	11	2,5	-	40	>50	-	40-60	25,6	4	2.323	1.719	1,35	2.000	1.600
DVORANA	P85-Test 4	11	2,5	-	40	>50	-	40-60	34,3	3	2.415	1.719	1,40	2.000	2.858
DVORANA	P101	11	2,5	-	40	>70	-	40-60	23,9	4	1.906	1.719	1,11	2.800	1.494
DVORANA	P74	11	2,5	-	40	>70	-	40-60	21,5	3	2.404	1.719	1,40	2.800	1.792
DVORANA	P76	11	2,5	-	40	>70	-	40-60	18,9	4	1.936	1.719	1,13	2.800	1.181
DVORANA	P110	11	2,5	-	40	>50	-	40-60	27,5	5	1.936	1.719	1,13	2.000	1.375
DVORANA	P127	11	2,5	-	40	>50	-	40-60	18,7	12	868	1.719	0,50	2.000	390
DVORANA	P105	11	2,5	-	40	>70	-	40-60	19,3	4	1.953	1.719	1,14	2.800	1.206
UPOV	B53-Test 1	8	5,0	45	22,1	20	85	42	41,0	24	878	572	1,53	441	427
UPOV	B53-Test 2	10	5,0	45	22,1	23	85	42	38,5	17	984	682	1,44	508	566
UPOV	B53-Test 3	11	5,0	55	27,0	32	90	44	19,7	12	1.092	1.013	1,08	863	410
UPOV	B53-Test 4	11	5,0	55	27,0	32	95	47	21,3	8	1.342	1.013	1,32	863	666
UPOV	B254	11	5,0	55	27,0	17	90	44	14,7	22	947	954	0,99	459	167
UPOV	B437	11	5,0	55	27,0	33	95	47	23,0	12	1.152	1.013	1,14	890	479
UPOV	B505	11	5,0	55	27,0	27	100	49	37,1	17	1.326	954	1,39	728	546
PRETOVARNA	3A-A10-Test1	15	5,0	100	49,1	7	95	47	21,0	27	1.462	440	3,32	343	194
PRETOVARNA	3A-A10-Test2	16	5,0	100	49,1	20	100	49	23,0	7	1.707	849	2,01	981	821
PRETOVARNA	3A-A10-Test3	17	5,0	100	49,1	35	100	49	23,0	13	1.870	879	2,13	1.717	442
PRETOVARNA	3A-A10-Test4	17	5,0	100	49,1	35	100	49	22,0	13	2.737	879	3,11	1.717	423
PRETOVARNA	3B-FB	17	5,0	100	49,1	15	100	49	18,0	18	876	879	1,00	736	250
PRETOVARNA	3B-F4	15,5	5,0	60	29,4	40	100	49	18,0	27	936	879	1,06	1.177	167
PRETOVARNA	3A-A7	15,5	5,0	60	29,4	37	100	49	18,0	14	954	879	1,09	1.089	321
PLODINE	40	11	5,0	100	49,1	>90	-	-	-			2.500		4.415	

L – duljina pilota u tlu; $M_č$ – masa čekića; H_{drive} – visina pada čekića tijekom zabijanja; $E_{t,drive}$ – teorijska energija zabijanja (= $M_č$ x H_{rive} x g); N_{25} – broj udaraca čekića za prodor pilota od 25 cm; H_{test} – visina pada čekića u dinamičkom testu; $E_{t,test}$ - teorijska energija testiranja (= $M_č$ x H_{test} x g); E_{test} – izmjerena energija testiranja, s – prodor pilota u dinemičkom testu; R_{test} – nosivost pilota izmjerena dinamičkim testom; R_{cal} – računska nosivost pilota, $E_{25,t}$ – teoretska energija utrošena za zabijanje zadnjih 25 cm pilota u zoni testiranja (= $M_č$ x H_{test} x g x N_{25}); $E_{25,test}$ – ekstrapolirana energija utrošena za zabijanje zadnjih 25 cm pilota prema rezultatima testa (= E_{test} x 250 mm/s)

The analysis of the results is shown in Figure 17. It can be noted that the measured values of pile load-bearing capacity are generally higher than the calculated values, with minor deviations attributed to local weakening in the foundation soil (P127-HALL pile and B254-UPOV pile). Statistical analysis of data (HALL, UPOV) shows that the mean value of the measured data is about 23 % higher than the calculated one, with a standard deviation of 0.24 %, which provides an excellent estimate of the characteristic load-bearing capacity of the pile in the value of the 95 % fractile in accordance with the recommendations of Eurocode 7. The diagrams also show the influence of the driving energy for the last 25 cm of piles on the pile load-bearing capacity and the settlement of the piles due to testing.

Figure 18 shows an analysis of the results from the aspect of estimating the design load-bearing capacity of piles (overestimated or underestimated load-bearing capacity). The results were compared with the database according to Bustamante and Gianeselli [3], based on which the aforementioned authors made a recommendation for calculating the load-bearing capacity of piles according to the CPTU test. There is an evident similarity in the obtained results, with most

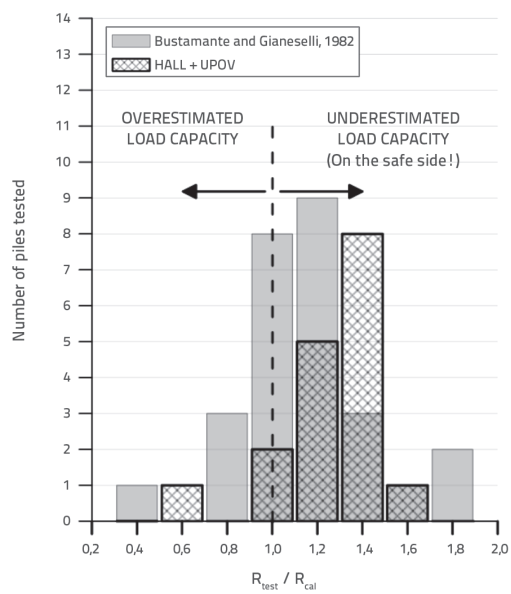


Figure 18. Results of pile testing for the Sisak HALL and Đakovo WWTP (UPOV) (ratio of measured and calculated pile load-bearing capacity, R_{test} / R_{cal}) and comparison with pilot test data according to Bustamante and Gianeselli [3]

of the results of this research clustering around a slightly higher value of R_{test}/R_{cal} = 1.4, while the result from the database of the mentioned authors is around the value of 1.2. The reason for this is attributed to the higher real load-bearing capacity of the pile base in compacted sands at the Sisak Hall location, which were calculated based on less reliable investigation works (SPT, DPH), so the calculated load-bearing capacity for these piles is underestimated. The above method for calculating the load-bearing capacity of piles according to CPTU testing [3] has also been assessed as the best method for calculating the load-bearing capacity of Frenki piles and MEGA piles constructed in similar geotechnical environments (see Vukičević et al. [14]).

5. Conclusion

This paper presents the experience in the implementation of driven reinforced concrete piles at four locations in Croatia. The geotechnical investigation results, which represent the basis for calculating the load-bearing capacity of piles in the design phase, are shown. Typical pile driving protocols and the results of 24 dynamic pile tests are presented. Based on the analysis of the results, rough guidelines were given for estimating the load-bearing capacity of piles based on the driving energy consumed and the expected settlement due to testing depending on the type of pile (floating pile or piles that are load-bearing on top). Using the example of two locations (Sisak HALL, Đakovo WWTP (UPOV)) where exceptionally high-quality exploratory work was carried out in all layers of material (exploratory drilling and laboratory testing to depths greater than the pile length, SPT, CPTU, DPH), statistical data processing has proven that the characteristic pile load-bearing capacity calculated according to modern methods given in the reference literature [2, 3] is safe in relation to the measured load-bearing capacity and corresponds to approximately the 95 % fractile of all investigated piles, which is in accordance with the recommendations of Eurocode 7.

This paper shows consistency in the applied methodology of research, calculation and control of pile load-bearing capacity, where it is important to emphasize that the key element for a quality assessment of pile load-bearing capacity is the implementation of quality investigation works: exploratory drilling and laboratory soil testing up to depths below the bottom of the pile, CPTU testing as the primary in-situ method for determining the mechanical characteristics of soft clays and powders and loose sandy materials, SPT and DPH testing in all materials, and especially in layers where it is not possible to embed a CPTU probe. High-quality investigation provides a reliable basis for selecting the optimal technical solution and assessing the load-bearing capacity of piles in accordance with the recommendations of Eurocode 7, while the dynamic testing method provides a relatively fast and reliable control of the actual load-bearing capacity of piles.

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