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Testing the integrity of reinforced concrete piles at the exit portal of the Kobilja Glava tunnel using a non-destructive method

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Abstract: Testing the integrity of piles is a key aspect of geotechnical analysis, and the application of non-destructive methods allows for a reliable assessment of the condition of piles without causing physical damage to the structure. This paper focuses on the application of the Pile Echo Test (PET) method for verifying the mechanical properties and quality of piles that serve as supports for portal structures. The testing showed that the measured velocities ranged from 4000 to 5000 m/s, with amplifications between 25% and 35%, indicating that the piles do not have serious structural issues and that no material degradation has occurred that would affect the load-bearing capacity or stability of the piles. By using the PET method, the integrity of the piles can be precisely determined, thereby enhancing the safety and long-term stability of portal structures. The results of this study confirm the importance of applying this method in geotechnical analyses as a reliable technique for verifying the quality of piles.

Key words: pile integrity, non-destructive methods, Kobilja Glava tunnel, ultrasonic testing, PET method

Ispitivanje integriteta pilota nedestruktivnom metodom na izlaznom portalu tunela Kobilja Glava

Sažetak: Ispitivanje integriteta pilota predstavlja ključni aspekt geotehničke analize, a primjenom nedestruktivnih metoda omogućuje se pouzdana procjena stanja pilota bez fizičkog oštećenja konstrukcije. Ovaj rad se bavi primjenom metode Pile Echo Test (PET) za verifikaciju mehaničkih svojstava i kvalitete šipova koji služe kao osiguranje portalnih konstrukcija. Ispitivanje je pokazalo da su izmjerene brzine u opsegu od 4000 do 5000 m/s i amplifikacije između 25% i 35%, što ukazuje da piloti nemaju ozbiljnije strukturne probleme i da nije došlo do degradacije materijala koja bi uticala na nosivost ili stabilnost šipova. Korištenjem PET metode, omogućeno je precizno određivanje integriteta pilota, čime se povećava sigurnost i dugoročna stabilnost portalnih konstrukcija. Rezultati ovog istraživanja potvrđuju značaj primjene ove metode u geotehničkim analizama kao pouzdane tehnike za verifikaciju kvalitete pilota.

Ključne riječi: integritet pilota, nedestruktivne metode, tunel Kobilja Glava, ultrazvučno ispitivanje, PET metoda

1. INTRODUCTION

The rapid development of urban areas in recent decades contributes to the increasing need to use underground space. The Kobilja Glava tunnel is a twin-tube tunnel that passes through the hill of the same name, on which there are about 500 residential buildings. The total length of the right tunnel tube is 635.10 m, of which 587.10 m is the length of the underground excavation. The temporary entrance portal of the right tunnel tube is located at chainage km 3+550.15, while the temporary exit portal is at chainage km 4+137.15. The total length of the left tunnel tube is 638.885 m, where the excavation length is 590.885 m. The temporary entrance portal of the left tunnel tube is located at chainage km 3+546.952, while the temporary exit portal is at chainage km 4+128.09. [1]

The Kobilja Glava tunnel is part of the main design for connecting the trans-European road network with the city's First Transversal Road in Sarajevo Canton. [2]

In the zone of exit portal of the Kobilja Glava tunnel, there is eluvial-deluvial cover up to 2 meters thick. The cover is underlain by a loosened geological substrate consisting of marly clays about 2 m thick. This layer is underlain by undisturbed geological substrate consisting of dark gray marls. The eluvial-deluvial cover consists of sandy clays mixed with fine debris and sandy clays, brown in color and plastic in consistency.

According to the material composition, the layer of undisturbed geological substrate consists of marls, dark gray in color and layered in texture. [3, 4] One of the most challenging and responsible engineering tasks is to excavate the underground rooms and tunnels, as well as to stabilize just excavated profile. [5] Modern design and construction of tunnels requires appropriate techniques and technologies to be applied in all design phases. [6]

Due to the low overburden in the zone of the portal structure and the demanding geotechnical and morphological conditions, the project requires the use of vertical reinforced concrete piles for the protection of the approach cutting at the exit portal of the Kobilja Glava tunnel. It is planned to make 50 vertical RC piles Ø120 cm in diameter. The layout of the reinforced concrete piles protecting the portal structure is shown in Figure 1. The maximum length of the piles is 20 m, while the minimum is 10.10 m (L = 20 m - 5 pieces; L = 17 m - 27 pieces; L = 15 m - 7 pieces; L = 13.80 m - 8 pieces; L= 10.10 m - 3 pieces). [7]

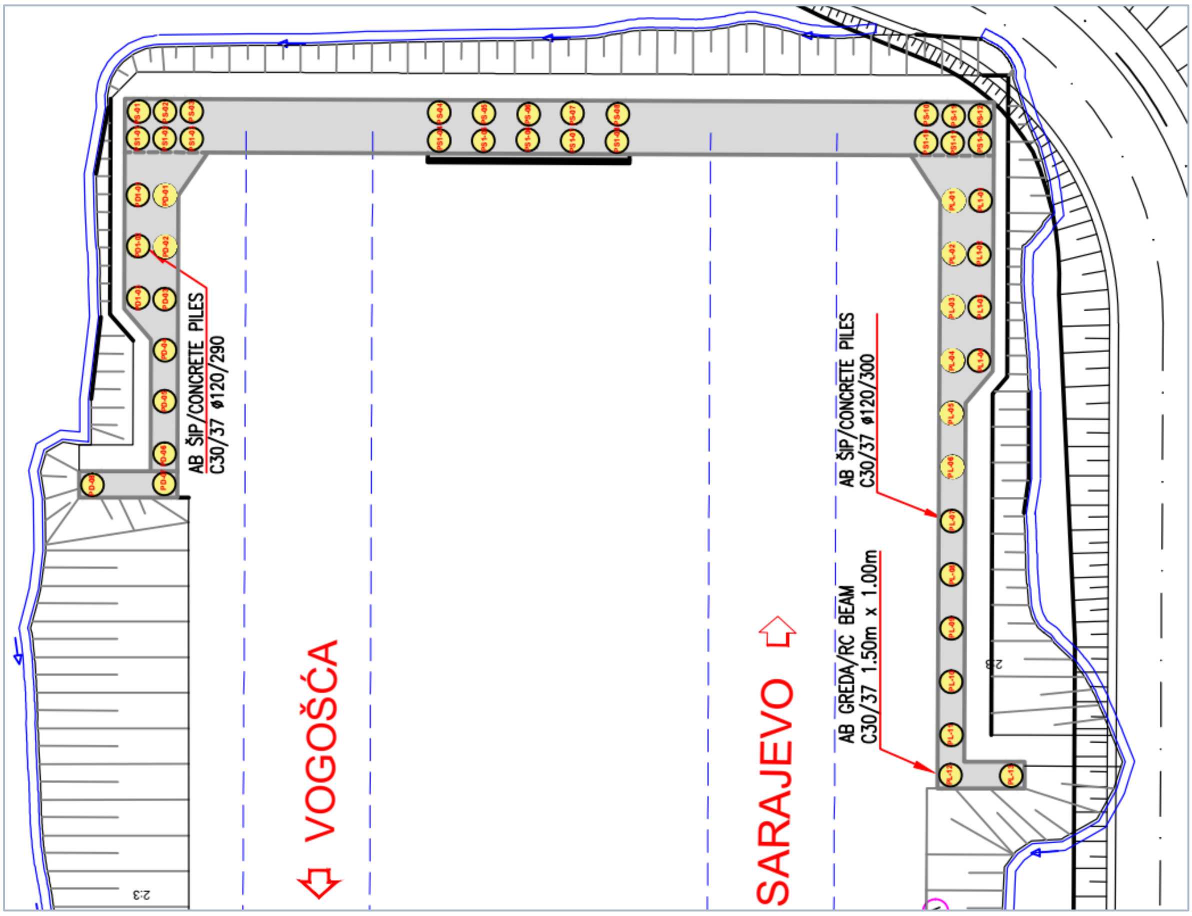


Figure 1. Layout plan of the exit portal approach cutting of the Kobilja Glava tunnel [7]

2. CONSTRUCTION TECHNOLOGY OF BORED PILES

Bored piles are widely used elements of deep foundations, especially in complex geotechnical conditions. The construction process begins with drilling a vertical borehole of a diameter and depth defined by the design, followed by reinforcement and concreting. The advantages of such piles include the possibility of construction in urban areas, minimal disruption of existing structures, and adaptability to different soil types. [8]

Pile drilling can be performed by various methods, depending on the characteristics of the terrain and the required pile performance. The most common methods include drilling with or without borehole casing, the application of stabilization using bentonite slurry, or the use of temporary pipes. Fully cased boreholes are used when there is a risk of collapse of the borehole walls, while partially cased boreholes are used in stable soil layers. [9]

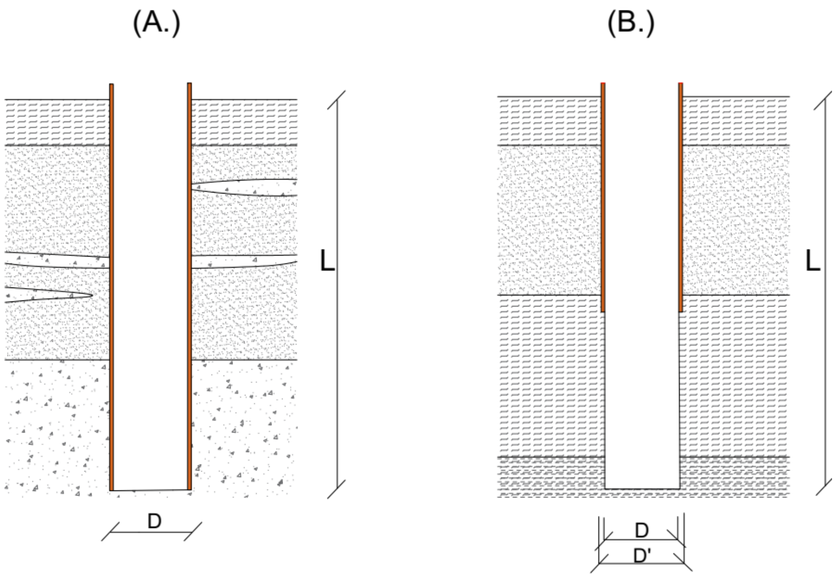


Figure 2. Borehole casing, A - complete, B - partial [10]

The drilling method with casing uses a temporary steel pipe to support the borehole walls. This technique is especially suitable for work in impermeable layers and non-cohesive soil. Alternatively, when using bentonite slurry, the borehole is stabilized with a liquid that prevents water penetration and collapse. [11]

Drilling is carried out using specialized drilling rig that includes various types of tools such as rotary drilling heads, spiral augers and buckets for extracting material (Figure 3). Modern machines allow for precise drilling control and continuous monitoring of process parameters. [12]

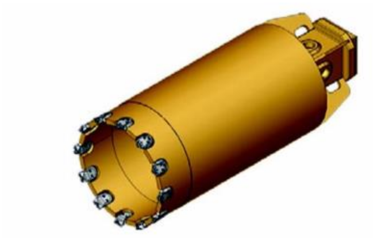
 *Auger for medium dense soil*	 *Rock cutting rig*	 *Box auger*

Figure 3. View of drilling rig for pile excavation [10]

The bottom of the pipe casing should advance faster than the speed of drilling, especially when working in cohesionless and muddy natural formations. This prevents the soil from breaking under the bottom of the pipe casing. Drilling is completed when the designed bottom is reached, which is controlled by two to three consecutive borehole height measurements with a graduated tape. The precision of the measurement is of the order of 1 cm. [13]

After reaching the designed depth of the borehole, the reinforcement and concreting phase is carried out. The reinforcement usually consists of previously prepared cages that are lowered into the borehole using cranes. The concreting of the piles is performed by the tremie method (Figure 4). The concreting begins by lowering the tremie pipe to a height of 20 cm from the bottom of the borehole. [14]

The concrete is placed from the bottom up to prevent mixing with water and ensure the continuity of the concrete mass. [15] The concreting technique by the tremie method involves pumping concrete through a pipe immersed in the fresh concrete at the bottom of the borehole, thus avoiding segregation of the material and contamination by groundwater. [16] The piles are concreted with concrete of plastic consistency, the characteristics of which are given in the design. When extreme exposure conditions are involved, class C30/37 or C35/45 concrete is usually used.

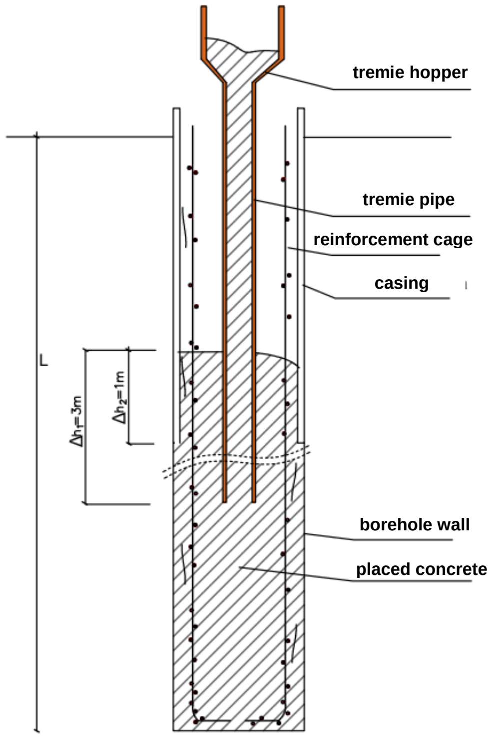


Figure 4. Schematic view of pile concreting [10]

For bored piles, the concrete must be poured at least 30 cm above the design level of the pile top to allow removal of contaminated concrete after hardening. This procedure helps to eliminate zones of poor quality concrete that may be affected by mud, groundwater, or impurities during pile construction. The contaminated top layer should be removed after the concrete has reached sufficient strength, usually no earlier than 72 hours after placement. [17]

Removal of the casing during bored pile construction involves airtight sealing of the top of the pipe to maintain internal pressure, introducing compressed air at a pressure of approximately two atmospheres, and activating a vibratory or oscillatory motion to reduce friction along the pipe wall. The pipe is then gradually extracted from the borehole using a crane. These measures are essential to prevent the borehole walls from collapsing and to preserve the integrity of the freshly placed concrete. [18]

The use of compressed air during the pipe extraction reduces friction between the pipe and the surrounding material, facilitating extraction. Additionally, positive pressure prevents soil or groundwater from penetrating the freshly placed concrete, ensuring better concrete quality and integrity. Studies have also shown that pressure-casting concrete results in a denser structure with fewer voids, improving the performance of the pile body. [19, 20]

For long casing pipes, the extraction is carried out successively, piece by piece, depending on the position of joints on the pipe. For shorter casing pipes, extraction is usually performed immediately after completing the concreting. During extraction of the casing, it is necessary to keep sufficient hydrostatic pressure within the borehole to prevent wall collapse and ensure continuous support of the concrete mass. [8]

During the construction of bored piles, special attention should be paid to quality control, which includes inspection of the reinforcement, control of the composition and temperature of the concrete, and continuous monitoring of the placing process. Modern control techniques include Pile Integrity Testing (PIT) methods and acoustic emission methods that make it possible to identify any discontinuities or defects in the constructed element. [18]

The choice of bored pile construction technology depends on a number of factors, including soil characteristics, groundwater level, bearing capacity requirements and site accessibility. Proper analysis and adjustment of the construction method are key to achieving high quality and long-term performance of the foundation system. [21]

3. TESTING THE INTEGRITY OF PILES USING A NON-DESTRUCTIVE METHOD

Due to the multistage and complexity of the bored piles manufacturing process, as well as the dependence of the results on the human factor, various defects can appear in the piles: zones of complete absence of concrete, porosity, decreased concrete strength, inclusions of natural soil. [22] The term "continuity of concrete" is understood as "an indicator of the quality of concrete, characterizing the continuity of the material and the absence of abnormal zones (sludge, voids)". [23]

The procedures for conducting pile integrity tests are defined by standards, which describe elements, criteria and test processes. One of the most commonly used non-invasive techniques for this purpose is the PET (Pile Echo Test) method, which has been in use since the 1970s. This method facilitates comprehensive analysis of pile continuity across all pile types and enables the detection of structural defects within the pile body. [24]

The USA ASTM standards are among the most detailed and reliable standards. They have clearly defined procedures, rules and quality control system. Pile integrity tests using the PET method according to USA standards are defined by ASTM D5882. [25]

Sonic integrity test (SIT) is often also called pile echo test (PET) in practice, and belongs to the group of low strain tests (LST). SIT is based on the theory of one-dimensional wave propagation through the pile, with the aim of determining: the actual pile length, the presence of defects and discontinuities, and the reduction in the cross section of the pile. [26]

This test is carried out on the principle of induction, propagation, reflection, refraction and reception of the waves in the pile. The wave induction is initiated by an outside action, by a hammer hit, so the external transmitted signal is of impulse type, in general. When an excitation occurs in an elastic material, waves are immediately generated starting from the excitation point, and they progress with a decrease in the amplitude of the disturbance oscillations. [27, 28]

The velocity of wave propagation through the pile can be calculated according to the following expression:

$$v = \sqrt{\frac{E}{\rho}} \tag{1}$$

where:

- v - is the wave propagation velocity (m/s),
- E- modulus of elasticity of concrete (Pa),
- ρ- material density (kg/m^3).

If the velocity (v) at which the wave travels within the pile axis is known, the depth of the defect or the end of the pile can be calculated according to the following expression:

$$L = \frac{v \cdot t}{2} \quad (2)$$

where:

- L - is the depth of the defect or the end of the pile (m),
- v - velocity of the wave propagation through the material (m/s),
- t- travel time of the wave to the reflecting point (s).

The pile integrity testing procedure consists of the following steps: [29]

- The surface of the pile head should be prepared ahead of the test. The surface of the pile head must be accessible and above water. All loose concrete, soil or other foreign materials resulting from construction should be removed from pile surface. If there is any type of contamination on the surface, it should be removed (using a grinder) in order to reach a solid and sound concrete surface.
- It is necessary to prepare three zones (if possible) of flat, dry concrete on the pile. The size of such zones should be approximately 100x100 mm for attaching the sensor (accelerometer) and for initiating waves with a special hammer on the concrete surface (Figure 5).

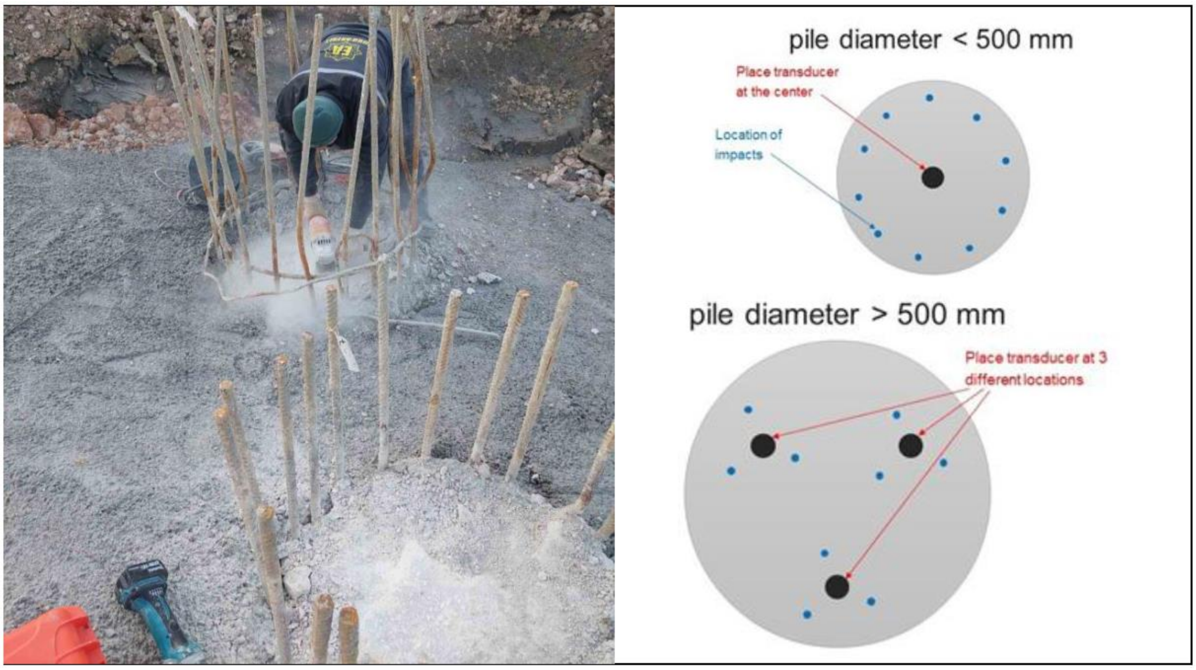


Figure 5. Preparation of the pile head for integrity testing, left - photo by authors, right [30]

- A successful application of the test method requires a firm connection between the sensor tip and the concrete surface (top of the piles). A thin layer of vaseline or putty is normally used for a firm connection between the sensor and the pile head (Figure 6). [30]

Figure 6. The method of placing the sensor on the pile head [30]

- At least three light blows are applied to each prepared place of the pile head with a special hammer (hammers weighing 0.5kg, 1.5kg and 3.5kg are used for piles of less than 1m in diameter, and hammers weighing 1.5kg, 3.5kg and 6kg are used for piles of more than 1m in diameter). The graph (reflectogram) of blow amplitude to the length of concrete pile dependence is represented on the display of the device. If the operator determines graphs to be acceptable for interpretation, these results are written into the memory of the device for additional processing. If the blows were either very strong or very weak, the device does not register any signal and it is required to repeat the blow. The blows are produced until the operator can interpret the registered graphs (reflectograms). [22]

A schematic view of pile integrity testing using the PET low strain method is shown in Figure 7. [31].

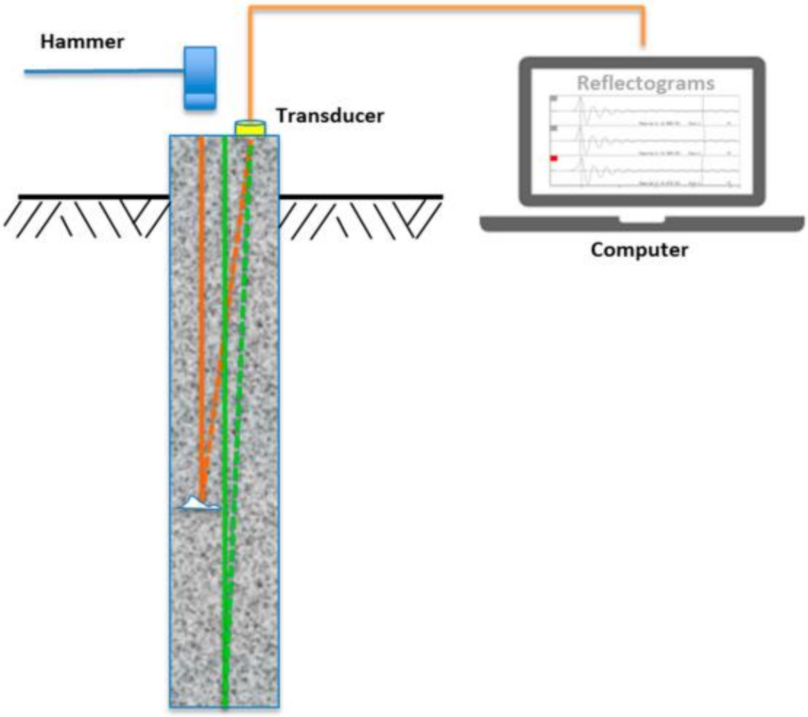


Figure 7. Schematic view of pile integrity testing using the PET method [31]

The interpretation of the reflectogram consists of the following steps: [32]

- if clearly visible fluctuations (oscillations in the wave propagation velocity) are observed on the reflectogram, this means that the pile has significant necking, cracking, incursions, geological influences, etc.;
- if such fluctuations are not significant, it means that the pile is without defects;
- if the reflectogram has sharp fluctuations, it means that the pile has serious cracking/necking in the place of the beginning of fluctuation.

A more detailed classification of the reflectogram can be carried out according to [33]:

- AA – a proper pile with positive reflections or such in which prior to reflection from the pile toe minor variations in velocity and deviations in the wave propagation velocity of not more than 5% of the average propagation velocity of the wave are identified;
- AB – the reflection from the toe is not clearly identified, but there are also no significant reductions in impedance (product of material density and velocity of waves propagating through it), where the possible reason for the lack of reflection from the toe is the high stiffness of the ground;
- PF – there is one or more negative reflections and/or there is at least one impedance decrease, and since the reflection from the toe is reduced, the impedance is lower than in the case of a defect where there is no reflection from the toe;

- PD – the wave propagation velocity deviates more than 5% from the average wave propagation velocity, indicating a possible defect in the pile, with one or more reflections masking the reflection from the pile toe;
- IR – considerably complex signal (response), which indicates, among other things, the poor quality of the concrete at the head of the pile and/or the test was conducted too early for the concrete to reach the required strength.

Figure 8 shows the SIT reflectograms of pile integrity obtained by the PIT-QFV equipment: a) regular pile, b) pile with impedance reduction in the initial part, c) the effect of increasing the impedance and soil stiffness, and d) pile built shorter than designed. [34]

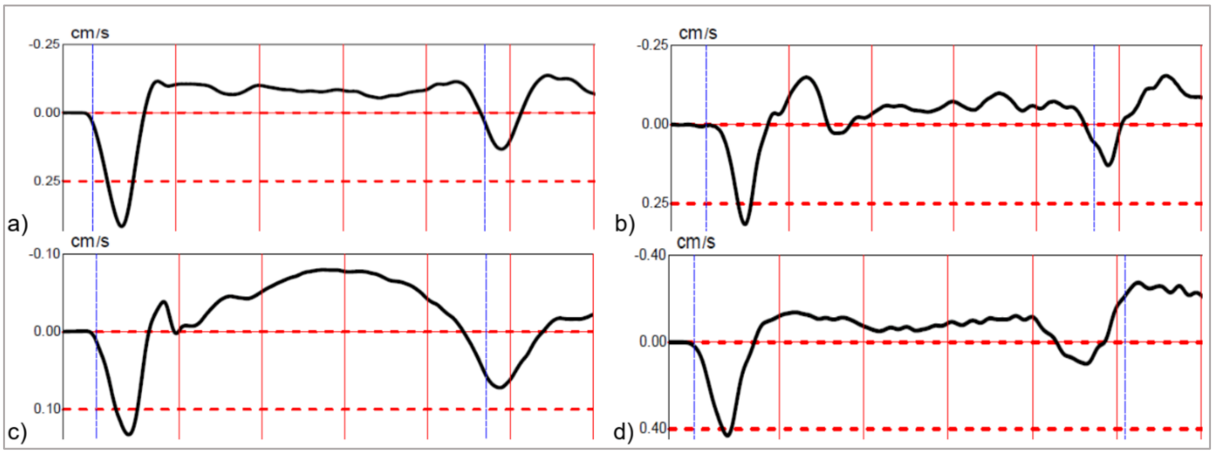


Figure 8. SIT reflectograms of pile integrity obtained by the U.S. PIT-QFV equipment: a) regular pile; b) pile with impedance reduction in the initial part; c) effect of increasing the impedance and soil stiffness; d) pile built shorter than designed [34]

3.1 Testing the integrity of piles at the exit portal of the Kobilja Glava tunnel using a non-destructive method

As was specified in the project documentation, 50 piles were constructed in the exit portal zone of the Kobilja Glava tunnel. The bored piles were drilled with rotary drilling technology using a Bauer machine (Figure 9).

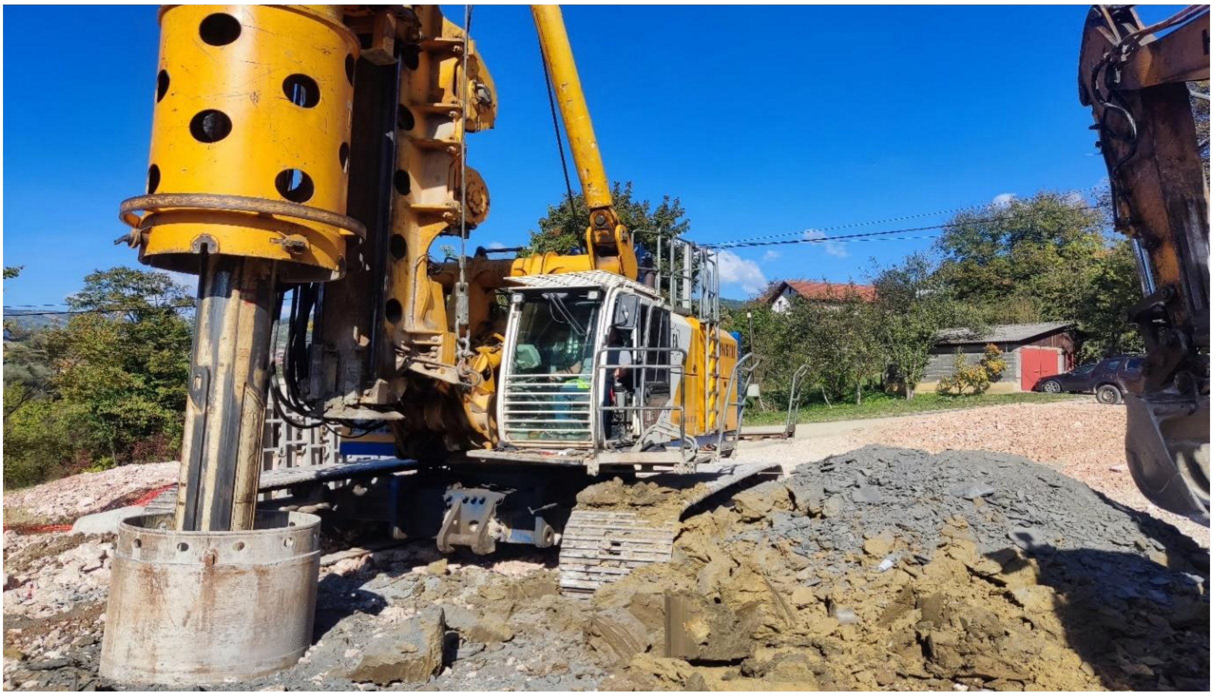


Figure 9. Drilling piles to protect the approach cutting of the exit portal of the Kobilja Glava tunnel (photo by authors)

When drilling the piles, each borehole was cased in the cover zone, down to the substrate (marl). The equipment used during pile integrity testing was FPrimeC - iPile, which consists of a hand held hammer, a sensor (accelerometer) and a device for recording, processing and displaying data. Before the start of the test, a detailed preparation of the pile head surface for integrity testing was carried out (Figure 10).

Figure 10. Preparation of piles for integrity testing (photos by authors)

After the detailed preparation of the pile heads, the pile integrity testing was conducted using the PET method on all the constructed piles in accordance with the ASTM D5882-16 standard (Figure 11).

Figure 11. Testing the integrity of piles using the PET method (photos by authors)

4. ANALYSIS AND TEST RESULTS

The pile integrity testing using a non-destructive method was carried out on all 50 piles constructed for the protection of the exit portal of the Kobilja Glava tunnel. The objective of the testing was to determine the presence of any defects, breaks, changes in section, actual length or inhomogeneity in the pile material in order to ensure their stability and durability for the purpose of protecting the structure.

Analyzing the obtained reflected wave signals, it was established that all tested piles showed a continuous and stable response, without noticeable anomalies that would indicate the presence of significant discontinuities. Reflected signals are clearly defined, with regular wave propagation along the entire length of the pile being registered, which indicates its complete structural integrity (Figure 12).

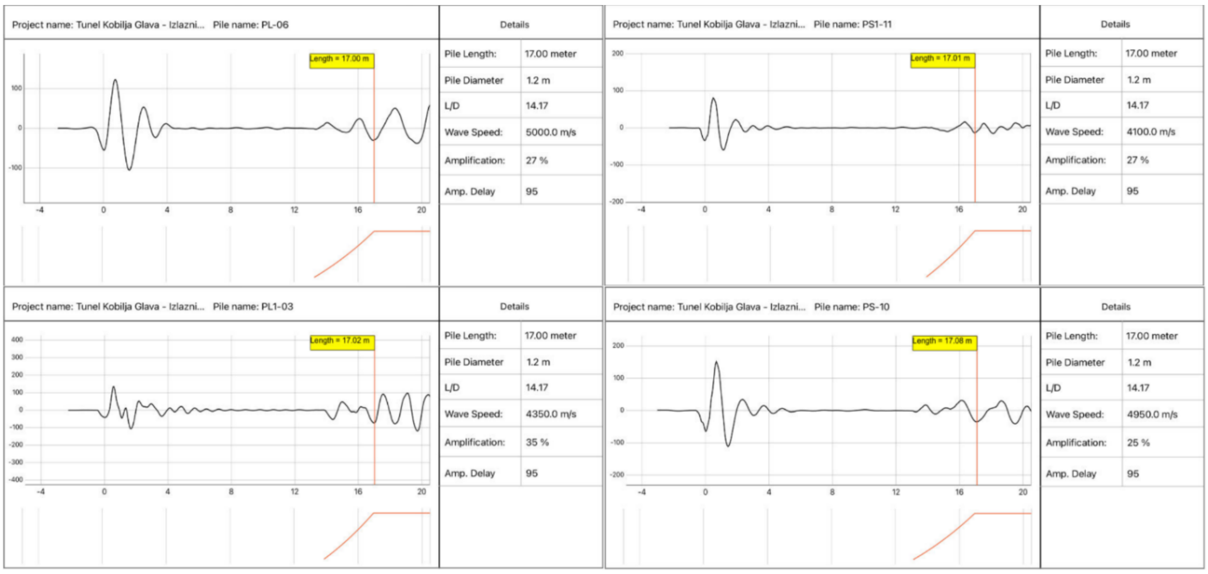


Figure 12. Reflectograms of pile integrity testing using the non-destructive impact pulse method (SIT)

Wave velocities in the range of 4000 m/s to 5000 m/s are indicative of concrete piles without serious structural problems. [34,35,36] Values below this range may signal potential defects or material degradation, which may affect the bearing capacity and stability of the piles. [34]

Signal amplification in the range of 25% to 35% indicates adequate wave reflection, which indicates good quality concrete without significant defects such as cracks or voids. With the help of linear or exponential amplification, it is possible to precisely detect and locate anomalies within the pile. [37,38]

According to research by Lee and White [39], similar methods were applied to infrastructure projects in Asia, where the results showed that ultrasonic techniques provided the most accurate pile homogeneity estimates. Also, according to the study by Brown et al. [40], the PIT method proved to be reliable in identifying serious defects in concrete foundations.

These findings further confirm the reliability of the applied tests and their relevance in assessing the integrity of the piles in this project. This information is exceptionally useful for evaluating the integrity, bearing capacity and long-term stability of piles in construction projects. [36]

5. CONCLUSION

Testing the integrity of the piles using the PET method was a key part of the foundation quality control within this research. All tested piles showed satisfactory results, which confirms their structural integrity and adequate performance in accordance with the design requirements.

The test results indicate that in the tested piles no significant defects, breaks or reductions in section that could affect their bearing capacity and long-term stability were detected. Continuous and clearly defined wave responses, without anomalies that would indicate inhomogeneities or dislocations in the material, confirm the quality of the performed works and the consistency of the applied pile construction technology.

This study confirms the effectiveness of the PET method as a fast, reliable and non-invasive technique for assessing the integrity of piles. The obtained results can serve as a basis for future research, improvement of test procedures and optimization of quality control methods in the field of foundation engineering. It is recommended to continue using this method in similar projects in order to ensure the long-term stability and safety of structures supported by deep foundations.

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