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REVIEW OF SCIENTIFIC INSIGHTS AND A CRITICAL ANALYSIS OF PILE CAPACITY AND PILE INTEGRITY TESTS

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ПРЕГЛЕД НА НАУЧНИТЕ ПОСТИЖЕНИЯ И КРИТИЧЕН АНАЛИЗ НА НОСИМОСПОСОБНОСТТА НА СТЪЛБОВЕ И ТЕСТОВЕ ЗА ИЗПИТВАНЕТО ИМ

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1. Introduction

Modern geotechnical engineering is based on a multidisciplinary approach to solving complex geotechnical problems through engineering-geological soil testing, laboratory analyses of physical and mechanical soil properties, developing constitutive models of soil behaviour, *in-situ* testing of geotechnical structures, experimental-laboratory testing of geotechnical structures and developing of analytical-numerical models for the analysis of geotechnical structures. In addition to structures formed only from the soil, geotechnical structures also include geotechnical injections, combination of soil and reinforced concrete (RC) elements, primary RC structures in the soil, structures from geotextiles/geogrids/geocells and the like. In the group of geotechnical structures, where the primary role is played by the RC structure in the soil, a specific place is taken by the issue of analyzing the capacity and integrity of piles. There are a large number of analytical and numerical methods developed for the purpose of determining the capacity and integrity of piles, as well as a large number of *in-situ* tests of real piles constructed in the ground. Also, a series of alternatives were developed for solving problems in the everyday engineering practice and scientific research. Despite of this, there are a number of unresolved issues in determining the capacity and integrity of piles, especially in case of piles in existing structures. This raises a number of questions, such as: what method, when and for what type of piles should be used? Answers to these questions can be found in a variety of publications, but there are a considerable number of questions to be answered in order to enhance the practice and scientific knowledge in terms of analyzing the capacity and integrity of piles, and develop new sophisticated and reliable solutions. This paper provides a summary of pile capacity and integrity tests for quick and reliable assessment and the choice of the type of test in different situations. The paper analyzes the most commonly used tests in practice, as well as tests of new generation which have been increasingly used and may replace some proven reliable tests.

2. Basics of pile testing

Pile tests can be divided into pile capacity and pile integrity tests. Pile capacity tests are aimed at determining the capacity at the pile base and pile shaft, as well as the cumulative capacity of the pile, so in terms of the stress state in piles the testing is conducted using high strain testing (HST). Pile integrity tests in terms of the stress state induced in piles are conducted using low strain testing (LST). Given that the HST approach is based on inducing high stress states and strains in the pile, it can lead to failure of the pile and inability to its use in service. Similar thing happens when using

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the HST method in case of excessive settlement. Based on the analysis of the pile quality before, during and after testing, the testing can be destructive (DT) and non-destructive (NDT). When a state of failure or near-failure occurs in the pile, then the HST test belongs to the group of DT tests. Due to the methodology of executing the tests, LST tests always belong to the group of NDT tests. Common to the pile capacity and pile integrity tests is that they are both carried out in *in-situ* real conditions in accordance with the pile testing program. The program includes several important phases: analyzing the macro location (construction site) where the piles will be tested, selecting the pile types to be tested (trial or permanent piles), analyzing the micro location (near the piles), planning the organization and accommodation of the testing equipment, analyzing safety and protection during the execution of tests. The equipment and the program of testing are much more complex in case of testing the pile capacity than in case of testing the pile integrity.

Due to their greater importance in practice, this study presents only tests of pile capacity against vertical load. These belong to the group of direct methods of testing, and all tests are carried out directly by inducing stress states in the pile, either through the pile head or in the pile depth. However, pile integrity tests belong to both direct and indirect methods, as in the former methods the testing is carried out by inducing stress states in the pile, while the latter allow other effects to be used in the interaction with the soil, such as wave propagation in the soil and pile.

Procedures of implementation of the pile capacity and pile integrity test are clearly defined by engineering codes. The most detailed and most reliable among these are the American ASTM (*American Society for Testing and Materials*) codes, which provide clearly defined test procedures.

3. Pile capacity tests

Methods of analyzing the capacity of piles can be divided to three groups: analytical, numerical and experimental (test). Analytical and numerical methods are based on solutions obtained by *in-situ* soil testing or laboratory testing of soil samples in order to determine its mechanical properties. For the higher reliability of results, the priority should be given to experimental methods, if possible. In most cases, pile capacity tests are carried out in two steps. The first step consists of testing a real pile, using some of the existing methods, and determining the force-settlement ratio through the curve of the test load. The second step is determining the discrete value of pile capacity using some of the existing mathematical methods of analyzing pile capacity. For some tests this second step is implemented by iteratively matching the signals obtained from the test. Load tests can be of static and dynamic nature:

- *static load test* (SLT),
- *bi-directional static load test* (BDSLT),
- *dynamic load test* (DLT),
- *pile driving test* (PDT),
- *hybridnamic pile test* (HPT),
- *statnamic pile test* (SNPT).

The *static load test* (SLT) belongs to the group of most reliable pile capacity tests, but in terms of preparation and procedure it is the most demanding test. The procedure of conducting this test is defined in ASTM D1143 / D1143M-07 codes [3]. Generally, there are two variants of conducting this test: testing with counterweight and testing with reaction piles (figure 1). In the first case, the counterweight should be adequately piled-up, which can be very heavy, depending on the bearing capacity of the pile. The weight of the counterweight should be 10% larger than the ultimate capacity of the pile. The reaction piles, used in the other case, are loaded with tensile force during the experiment. The head of the pile is exposed to the incremental increase of action of the piston of a hydraulic press. Due to the displacement of the piston and the opposition of the counterweight or the reaction piles, the tested pile is pressed in the soil. The pile head settlement is monitored using a comparator. Using geodetic devices the pile settlement is monitored, and the final result is determined by comparing the values. The conducted test yields with a test load curve as a force-settlement ratio, while the capacity of the pile is determined by one of the analytical methods. Compared to other tests, this test requires much more time for preparation and execution in order to obtain high-quality solutions.

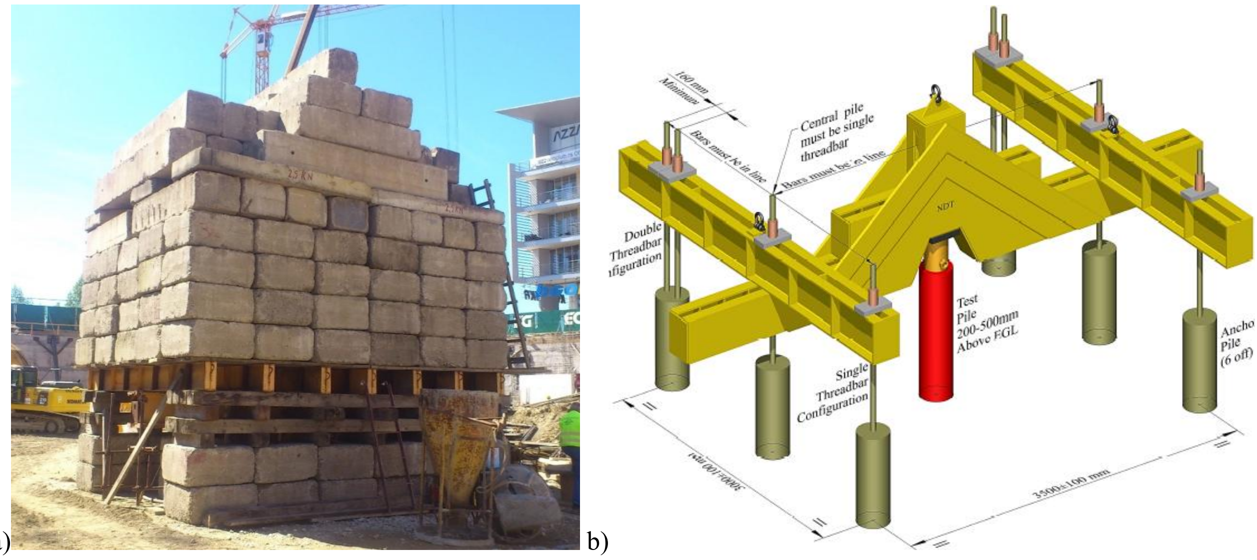


Figure 1. *Static load test* (SLT): a) test with counterweight (photo by the author from the test site), b) testing using reaction piles [17]

The *bi-directional static load test* (BDSLT) is a new generation test which does not require using counterweight or reaction piles [28]. Specific to this test is that the main part of the test equipment is built in the pile body, so that these piles cannot be further used (figure 2). The test is prepared by welding two circular steel plates to the prepared reinforcing cage, between which the *Osterberg* cells are placed (press or presses) along with hoses for the hydraulics and extensometers, after which the cage is filled with concrete. The test is conducted when the concrete is hardened. Under the action of hydraulic pressure fracture occurs in the concrete at the place where the *Osterberg* cells are located, so that the pile is pushed upwards, and then downwards. The instruments monitor the pressure in the *Osterberg* cells and the pile deformation (settlement). The pile settlement is also monitored with geodetic devices, so that the final results are determined by comparing the values. The test ends when the maximum displacement of 150 mm, or the maximum load as defined by the test project, is reached. This test requires a certain amount of time for preparation and execution, and the equipment and piles used for the test cannot be used for further testing and operation.

The *dynamic load test* (DLT) is based on determining the pile capacity under externally induced dynamic action. The test procedure is defined in ASTM D4945-08 codes [1]. There are two alternatives to conducting the test: testing with the own system for lifting the weight, and testing with an auxiliary system for lifting the weight to a certain height (figure 3). In both cases the weight is exposed to free fall from a certain height, with the dynamic action in the pile being induced by the blow of the weight on the pile head. This is enabled by system which raises the weight to a certain height and stops it there with brakes. The equipment can be connected to the pile head or mounted on the surrounding ground (for larger weights). Accelerometers and strain gauges are mounted in the zone of the pile-head for acquiring the signal which is subsequently processed by spectral matching to determine the total capacity, as well as the capacity along the base and shaft. Compared to the other tests, this test requires shorter the time for preparation and the execution, and provides medium-quality solutions. After the test, in some cases, the pile can be further used.

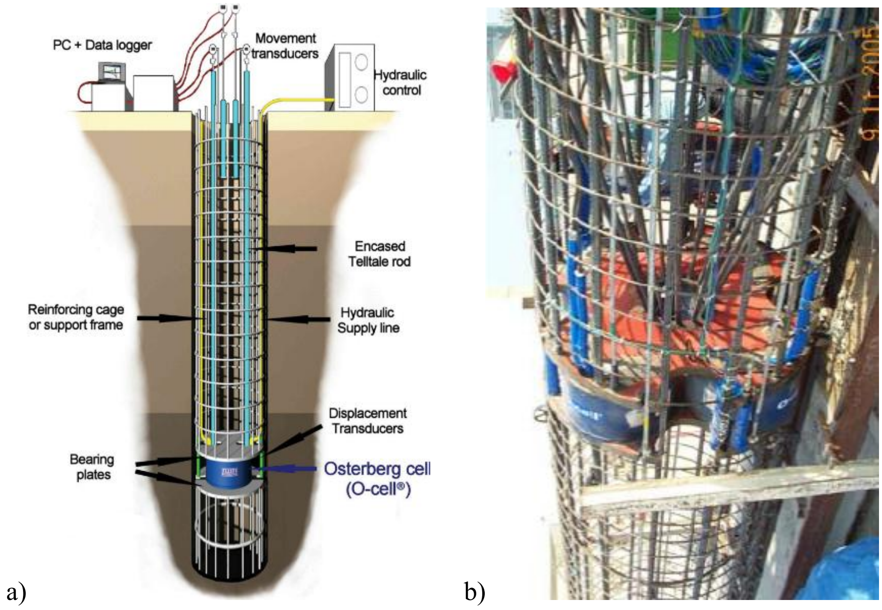


Figure 2. *Bi-directional Osterberg static load test* (BDSLT): a) schematic view [15], b) O-cells connected with the instruments [24]

The *pile driving test* (PDT) is based on the analysis of capacity and monitoring the behaviour of the pile during the driving. The external dynamic excitation is achieved using a pile driving machine (figure 4). The test can be performed with driving the pile under blows (cyclic process) or vibrations. The test procedure is defined in accordance with the ASTM D4945-08 codes [1]. The advantage of this dynamic test over the *dynamic load test* (DLT) is that here the reaction force in the pile base and pile shaft can be monitored and determined in various stages of driving the pile in the soil. Other effects can also be monitored, such as checking the pile integrity (large fissures, damage, fracture etc.). Through the phase of construction, this method inspects the pile capacity in several steps. Although a complex test which requires a larger volume of work during data processing, the quality of solution obtained by the PDT method is higher than those obtained by using the DLT method, while after the test the pile can be further used.

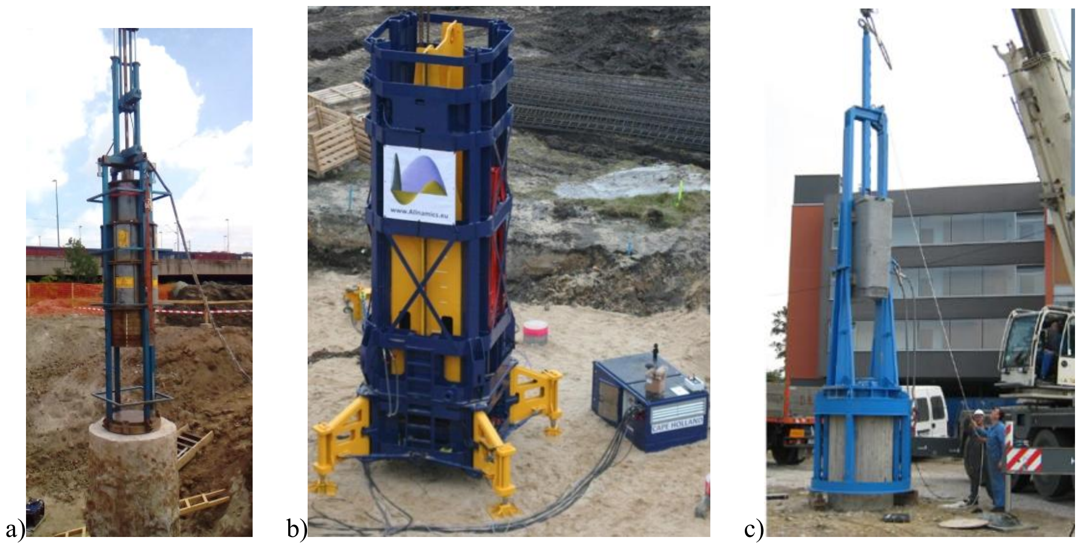


Figure 3. *Dynamic load test* (DLT): a) test with the own system for lifting the weight with the equipment connected only to the pile head (photo by the author from the test site), b) test with the own system for lifting the weight with the equipment mounted on the surrounding soil [14], c) test with an auxiliary system for lifting the weight to a certain height [12]

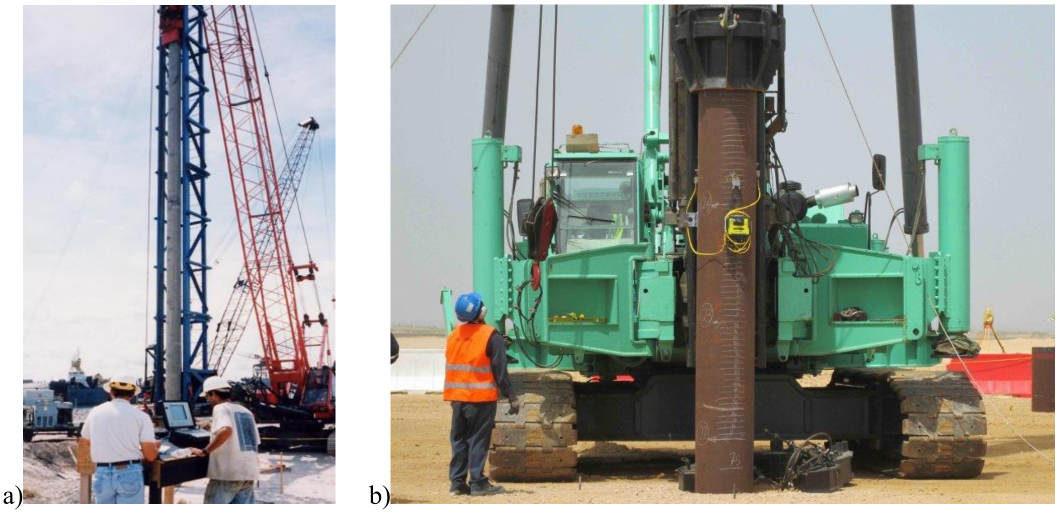


Figure 4. *Pile driving test* (PDT): a) pile driving machine under blows, the mounted equipment for data acquisition, and the test pile [13], b) vibration pile driving machine, the mounted equipment for data acquisition, and the TP [20]

The *hybridynamic pile test* (HPT) is based on a combination of the *static load test* (SLT) and the *dynamic load test* (DLT), while the propagation of waves in the pile can be ignored, so that the stress state due to the external excitation is very similar to the stress state obtained in the *static load test* (SLT) (figure 5) [16]. Thanks to the developed hybridynamic cushion, the duration of applying the external excitement (weight) to the pile head is considerably longer than in the case of the DLT. The hybridynamic cushion is of honeycomb shape and consists of steel plates, cells filled with air and elastomers with the properties of rubber. This cushion prevents the creation of additional blows in when the weight bounces off from the pile head, which adversely affects the testing. In addition to hybridynamic cushion, after the action of the external excitement (weight) and its bouncing off from the pile head, some *hybridynamic pile tests* (HPT) solutions retain the weight using a braking mechanism, preventing additional blows from occurring. The time required for the preparation and execution of the HPT tests is almost identical to that required by the DLT, but it also requires a relatively high level of safety to be provided. The quality of solutions provided by this method is higher than those obtained using the DLT, and after the test, in some cases, the pile can be further used.

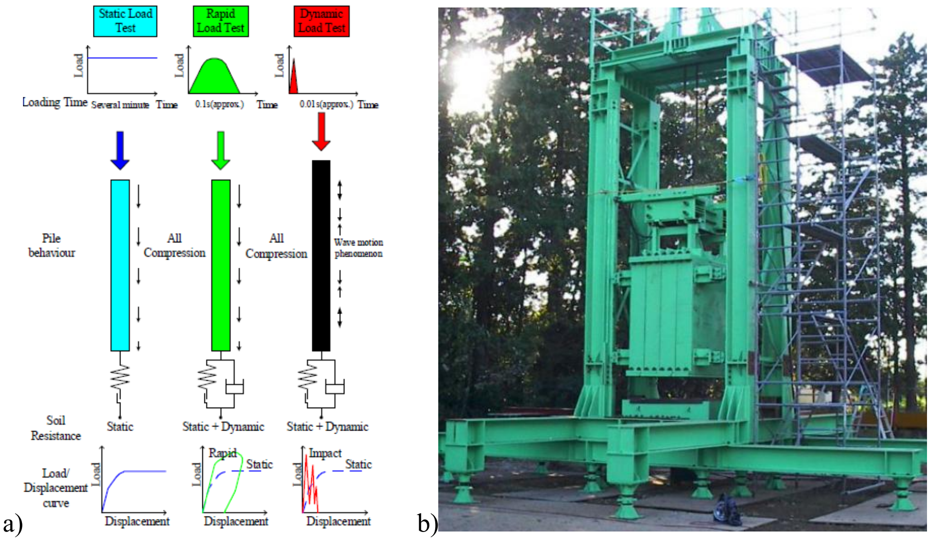


Figure 5. *Hybridynamic pile test* (HPT): a) comparison of static, hybridynamic and dynamic pile tests, b) equipment for conducting the *hybridynamic pile test* [16]

The *statnamic pile test* (SNPT) is based on the combination of static (SLT) and dynamic (DLT) pile tests, but the external excitation which acts on the pile head is realized through the explosive action of fuel (figure 6) [6]. There are two alternatives for this test. In the first alternative the weight is lifted vertically upward under an explosive action and then falls freely back on the gravel that lies between the pile head and the weight. In the second alternative the weight is lifted vertically upward under an explosive action and then restrained with a braking mechanism at a certain height, preventing it from falling freely back. In the first case the gravel reduces the effect of dynamic action and the subsequent blows that would be realized by the weight bouncing off from the pile head, while the second case takes into account the vertical downward pressure of the pile as a result of the upward motion of the weight. Due to the explosive effect when lifting the weight vertically upward, the reactive force applied to the pile head is up to 20 times greater than the weight's own weight. The time required for the preparation and execution of the test is almost identical to the time required for the dynamic load test (DLT). A high level of safety during this test is ensured, although the test is carried out using explosive material. The data processing and interpretation is more complex, and the quality of the obtained solution is higher than in the case of the DLT method. The possibility of using the pile in service after conducting the experiment is debatable.

4. Pile integrity tests

Most of the pile integrity testing methods are based on the propagation of waves through the pile and soil, and can generally be divided in two groups: direct and indirect. The state of pile integrity can be inspected directly, while indirect methods are used to inspect the state of pile integrity through the soil. Both cases are characterized by the fact that the signals obtained by testing are subsequently processed and analyzed using the time, frequency or time-frequency domain. The signal processing is based on scaling, filtering, spectral matching, generating and transforms. Generally, pile integrity tests can be divided as follows:

- *pile integrity test* (PIT) or *sonic echo test* (SET) or *pulse echo test* (PET),
- *singlehole sonic logging* (SSL),
- *crosshole sonic logging* (CSL) or *crosshole acoustical testing* (CAT),
- *crosshole sonic logging tomography* (CSLT),
- *parallel seismic method* (PSM),
- *gamma-gamma logging* (GGL),
- *thermal integrity profiler* (TIP).

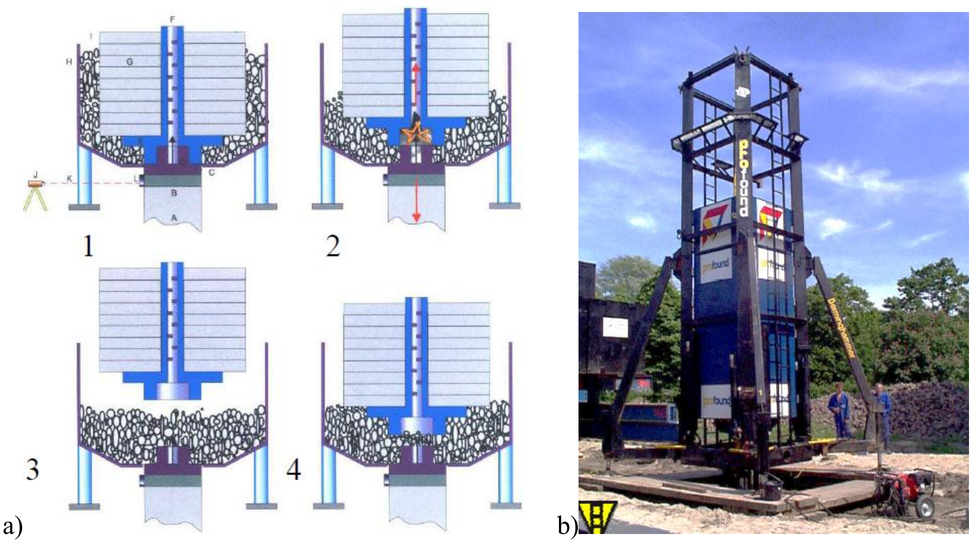
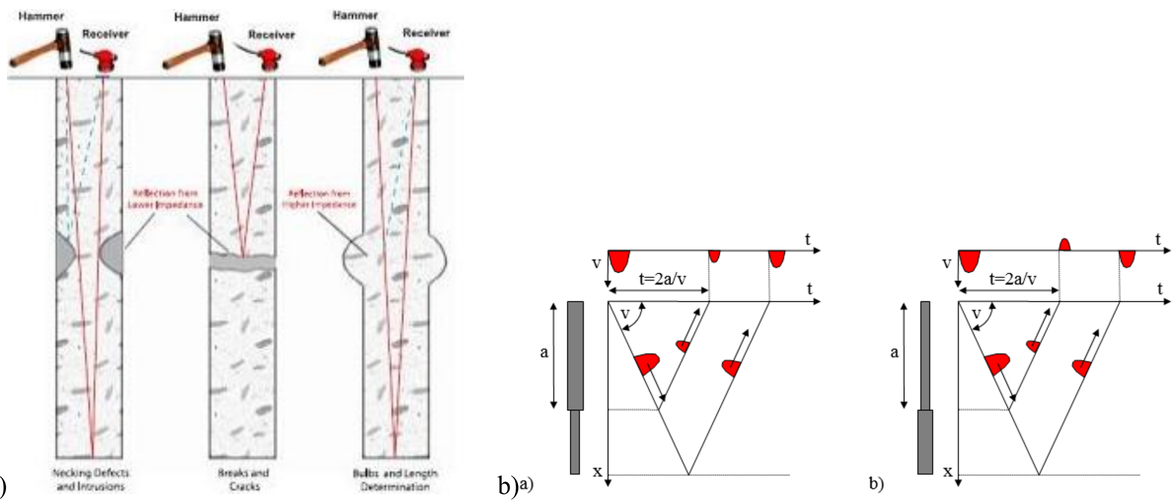


Figure 6. *Statnamic pile test* (SNPT): a) schematic view, b) equipment for conducting the statnamic pile test [10]

The *pile integrity test* (PIT) is based on the theory of wave propagation through the pile in order to determine the defects/discontinuities, and the length of the pile. The test procedure is defined in the ASTM D5882-16 codes [5]. This test is carried out on the principle of induction, propagation, reflection, refraction and reception of waves in the pile (figure 7) [8]. The induction of waves is initiated through an external action by striking hammer, so that the transmitted signal has the character of an impulse. Propagation of waves through the pile is carried out after initiating the wave, from the head to the pile base, and reversely. The effect of reflection occurs at the interface of two different media, in this particular case at the location of the pile base-soil interface, where the wave propagates towards the pile head. Wave refraction is the effect of refraction of waves at the interface of two different media, such as the interface between the pile base and pile shaft, and the ground. Given that the length of the wave which is initiated is longer than the pile diameter, the wave propagation through the pile can be considered by applying the one-dimensional theory of wave propagation in solid medium. The record of changes in the propagation of waves through the pile in time is presented through reflectograms. Generally, changes in the reflectogram occur as a result of changes in the pile base, changes in diameter along the pile body, partial inclusion of soil in the pile domain, fissures, uneven quality of the pile material, uneven in soil layers, and the influence of reinforcing steel in the pile (heavily reinforced piles). Compared to other tests, this test is characterized by the following: it is a very fast, reliable and inexpensive test for determining the length of the pile, ease of data processing, does not require a high levels of training, and is able to detect defects/discontinuities in the pile, but speaking about their actual dimensions along the pile and at the level of the cross section is disputable.

The *singlehole sonic logging* (SSL) is used to analyze the defects/discontinuities in the pile, and is based on wave propagation by using a hydrophone which houses the transmitter and the receiver (Figure 8). The waves are emitted through the transmitter, they propagate through the pile, they are reflected in places of contact with the ground and caught with the receiver. Since the hydrophone is lowered vertically downward along the pile, the signal which is obtained through the receiver is continuously monitored. Thus, this test is mainly used for the direct analysis of defects in the cross section, so that the integration of responses provides a more complete picture of the state of the pile. This single tubelet echo sound test is mainly used in smaller diameter piles or piles where the limitations allow only a small cross-sectional area to be used for testing. Compared to other tests, this test is characterized by the fact that is should be prepared as early as in the stage of construction of the pile, since the tubelet must be installed in the pile body, it is more reliable than the *pile integrity test* (PIT) but more demanding in terms of quantity of data to be processed, requires a relatively high level of training, it can detect defects / discontinuities in the pile, but is less effective than the other methods, which are described below.



a) b)

Figure 7. *Pile integrity test* (PIT): a) schematic view [19], b) propagation of waves in pile with a discontinuity [27]

Similar to *singlehole sonic logging* (SSL), *crosshole sonic logging* (CSL) is also based on wave propagation by using a hydrophone, but here the transmitter and receiver are separated (figure 9). The procedure of performing these tests is defined in ASTM D6760-08 codes [2]. The transmitter and the receiver are placed in two separate tubelets, so that the state of the pile along

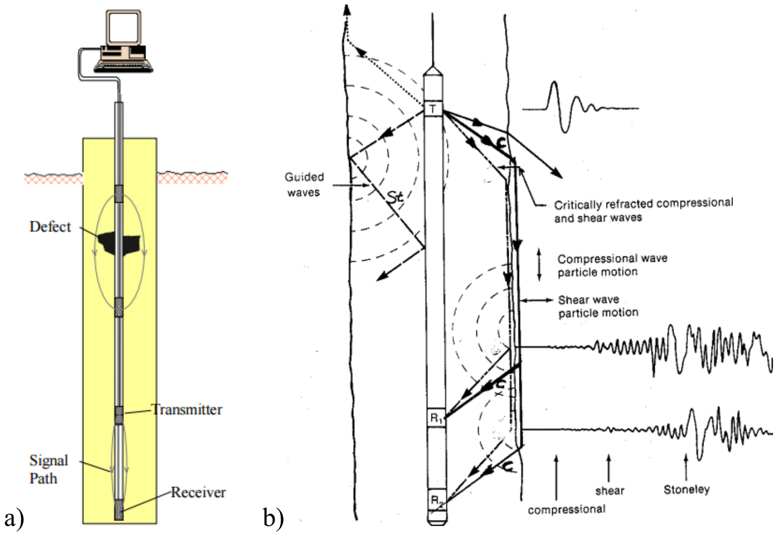


Figure 8. *Single hole sonic logging* (SSL): a) schematic view [7], b) waves are emitted through the transmitter, propagate through the pile, reflect in places of contact with the ground and are accepted by the receiver [18]

its cross section is monitored by gradually moving the transmitter and the receiver vertically in downward/upward direction. Integrating the analyses obtained along the pile provides a complete picture of possible defects/ discontinuities, whereby smaller defects can also be detected, such as fissures, cavities, intrusion of water / soil, as well as concrete nests (honeycomb). The largest number of defects is identified in the vicinity the tubelet, but for larger diameter piles the test can be conducted using a larger number of tubelets. This produces a higher quality picture of the state of pile integrity. Compared to other tests, this test is characterized by the fact that is should be prepared as early as in the stage of construction of the pile, since the tubelets must be installed in the pile body, it is more reliable than the *pile integrity test* (PIT) and the *single hole sonic logging* (SSL), but also more demanding in terms of quantity of data to be processed, it requires a relatively high level of training, and can detect a larger number of small defects/discontinuities in the pile.

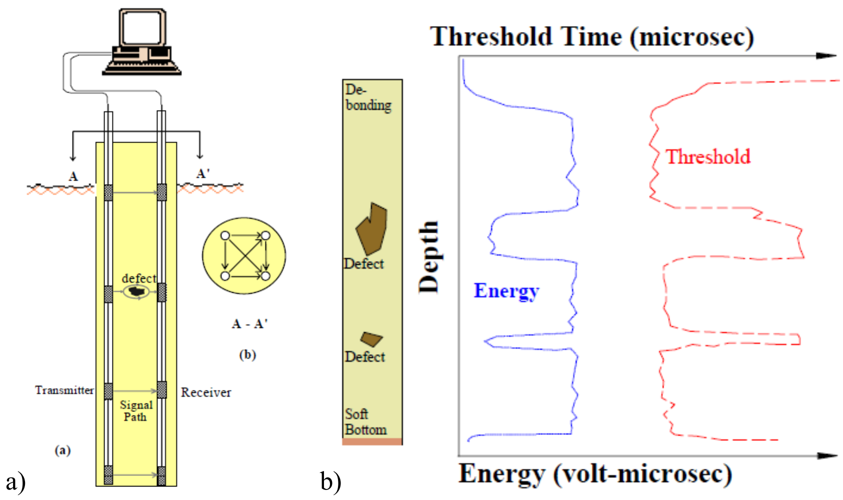


Figure 9. *Crosshole sonic logging* (CSL): a) schematic view, b) presentation of identification of defects in the pile [7]

2D or 3D *crosshole sonic logging tomography* (CSLT) is the further enhanced version of *crosshole sonic logging* (CSL) with two or more tubelets installed in the pile. Instead of recording the signals emitted directly between the transmitter and receiver, this test also records the signals emitted at different angles. Since the signals are in fact emitted in a large number of directions and at different angles, subsequent processing and reconstruction provides 2D and 3D views of the state in the pile, so that defects/discontinuities can be visually clearly distinguished (figure 10). This 3D pile model with defects/discontinuities can be used for further numerical analysis using the *finite element method* (FEM), with the prior generation of an appropriate network of 3D solid finite elements. Compared to the other tests, this test is characterized by the fact that is should be prepared as early as in the stage of construction of the pile by installing several tubelets, this test is more reliable than the other pile integrity tests (PIT, SSL and CSL), requirements regarding the quantity of data to be processed are further increased, it requires a relatively high level of training, and it can detect very small defects/discontinuities in the pile.

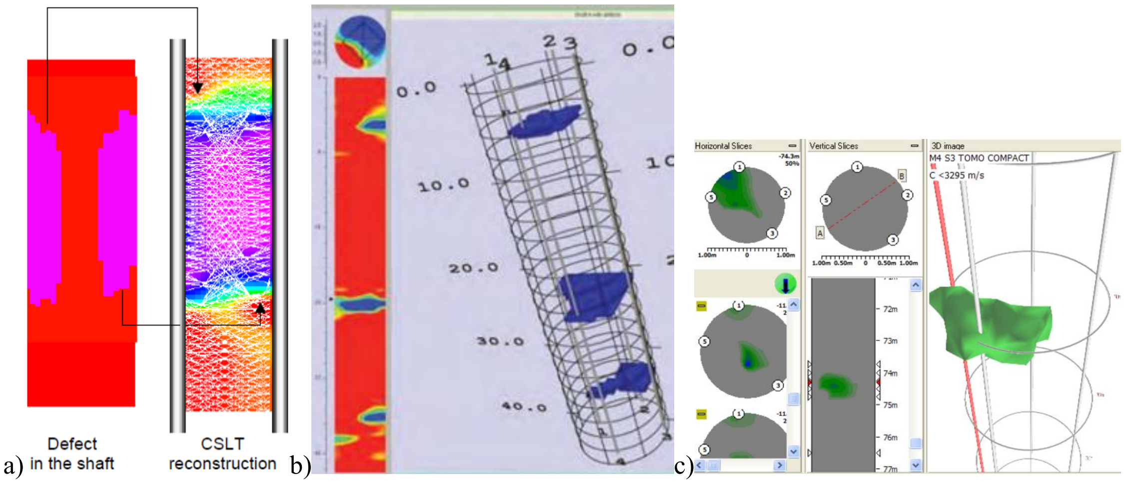


Figure 10. 2D or 3D *crosshole sonic logging tomography* (CSLT) with 2D or 3D display of discontinuities and defects in the pile: a) schematic view of reconstruction of defects in the pile using CSLT [25], b) 3D model of reconstruction of defects in the pile using CSLT [23], c) 3D model of the highlighted defect in the pile using CSLT [22]

The *parallel seismic method* (PSM) is a procedure where the presence of defects/discontinuities in the pile are detected in an indirect way, based on the propagation of waves through the ground, with the pile length being also determined (Figure 11). This test is particularly useful for determining the depth of the existing piles in the structure.

By applying external excitations to the pile head vibrations are created which are transmitted through the ground, where using a hydrophone or receiver the signals are recorded in digital format which are then subsequently processed. The actual pile length and the possible presence of defects/discontinuities are determined by analyzing the series of recorded signals.

Compared to the other tests, this test is characterized by the relative quickness of preparation because there are no tubelets to be installed in the pile, it is mainly used to analyze the length of the pile in cases when the *pile integrity test* (PIT) cannot be easily conducted, it does not require high level of training, and it can detect only larger discontinuities in the pile while small defects/discontinuities remain undetected.

The *gamma-gamma logging* (GGL) is based on the emission and propagation of gamma rays though the pile, analyzing the density/porosity of concrete and thus identifying the defects/discontinuities (figure 12). The procedure of *gamma-gamma logging* (GGL) is defined in codes [26]. The test is conducted by moving a transmitter and a receiver probe vertically upward/downward through one or two tubelets (completely dry). On the basis of the reference value of the density of concrete, deviation for each step of measurement is determined and a diagram constructed presenting the high density, the low density and the transitional zone. Compared to the other tests, this test is characterized by the fact that it should be prepared as early as in the stage of construction of the pile, given that the tubelet (tubelets) must be installed in the pile body. This test is more reliable than the *pile integrity test* (PIT), requires intermediate level of training, it can detect defects/discontinuities in the pile, but not so well as the previously shown methods.

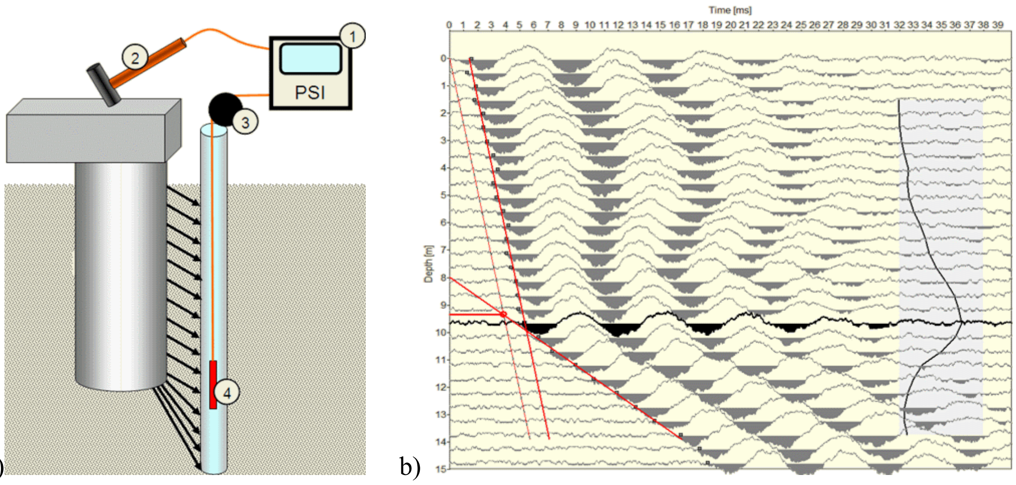


Figure 11. *Parallel seismic method* (PSM): a) schematic view, b) a series of recorded signals based on which the actual pile length and the possible presence of defects/discontinuities is determined [21]

The *thermal integrity profiler* (TIP) is based on the analysis of temperature of hydration of cement in order to identify defects/discontinuities in the pile (Figure 13). The procedure of thermal integrity profiler (TIP) is defined in ASTM D7949-14 codes [4]. Similar to previous tests, this test is conducted using tubelets through which the probe moves vertically downwards/upwards. Compared to the other tests, this test is characterized by the fact that it should be prepared as early as in the stage of construction of the pile, given that the tubelets must be installed in the pile body. Compared to the CSL and GGL test, this test is able to analyze the entire cross-sections along the pile and indicate the zones of concrete of higher and lower quality. It requires intermediate level of training, and can detect very small defects/discontinuities in the pile.

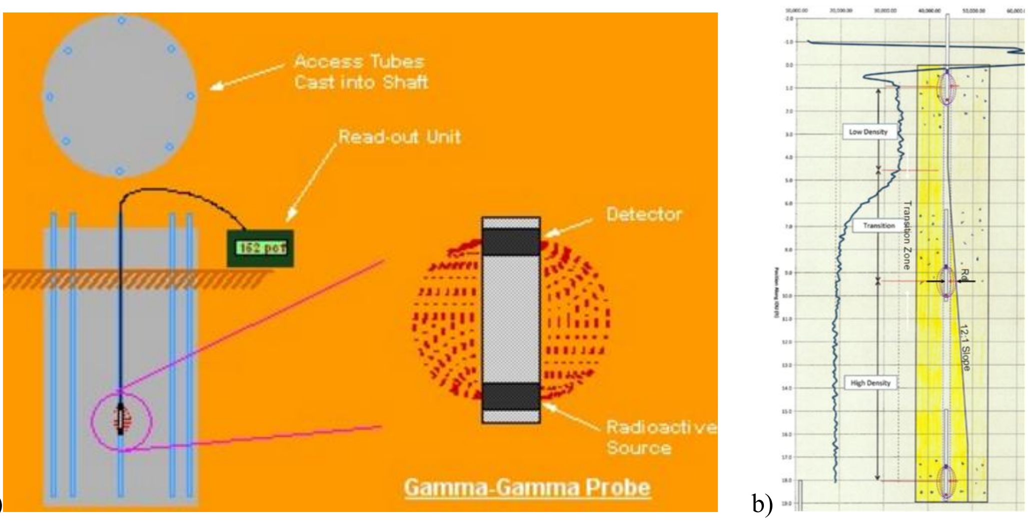


Figure 12. *Gamma-gamma logging* (GGL): a) schematic view, b) identification of defects in the pile by analyzing the density/porosity of the concrete [9]

5. Conclusion

Given the complex nature of the issue, a review of scientific insights and critical analyses of pile capacity and pile integrity tests cannot be presented in detail with a single article. Thus, this paper presents only the basic elements and provides a brief critical analysis of tests. The complex issue of testing the piles is a multidisciplinary problem that requires commitment, not just from engineers and scientists of civil engineering, but also from engineers of geology, geomechanics, geophysics, as well as software and electrical engineers for analyzing and interpreting the signals. On the other hand, the development of new technologies and their implementation in pile testing requires continuous education for engineers, as well as specialization in certain fields. In general, it can be said that the biggest problem in testing the pile capacity is inspecting the piles which are in service conditions and in which determining the capacity and integrity is the most difficult to conduct. The existing pile capacity tests are mainly intended for testing newly built piles, while certain pile integrity tests can be used for piles that are already in service. Since settlement represents the key problem in structures which are already in service, in most cases instead of conducting pile capacity tests, new piles are directly constructed or the old ones reinforced.

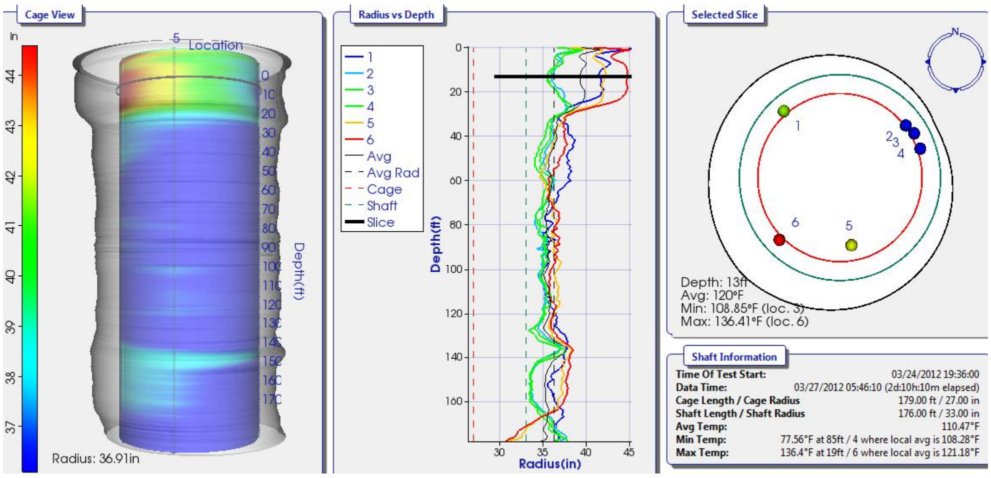


Figure 13. *Thermal integrity profiler* (TIP) - test results [11]

Pile capacity tests which will be developed in the future, need to demonstrate more effectively and in more details the distribution of stress state along the pile shaft and pile base, and to indicate the activation of capacity of the newly designed and existing piles. The key solution is to analyze the mobilization of soil around the pile during the service for the level of limit capacity state, which could further affect the design and form pile capacity tests. Regarding the pile integrity tests, their development is going in the direction of software-hardware engineering and signal theory and signal processing. The problem is in the installation of tubelets in the pile which certainly can further affect the pile capacity, especially if their number is high (up to several dozen). In this sense, the development of new pile integrity tests should be directed towards developing low-cost sensors that would be connected by conductors of small cross-section or wirelessly. A higher number of sensors would be built into the pile body during construction, which would communicate with the data processing server wirelessly or maybe through a cable. Also, there is a possibility for sensors embedded in the pile body to have a wireless or maybe cable communication with a GPRS device mounted on each pile, which would emit a signal to the main data processing server in a completely different place than the location where the pile is built. In this way, pile integrity tests would be conducted very efficiently, and even real time monitoring could be conducted in service conditions.

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