NDT PILE TESTING METHODS

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1. INTRODUCTION

Dynamic development of pile technologies, observed in the recent years, presents a serious challenge for the participants of construction process: it is inevitable to ensure quality control of running works or acceptance investigation of piles and columns made in new, and often not yet described by any standards, technologies. That refers, above all, to the control of length and continuity of those elements. It has to be noticed that ferroconcrete piles and soil-concrete columns belong to those few structural elements, the control of which is very difficult, since, apart from the element's head, there is no access to them. Polish Code of Practice PN-83/B-02482 [1] does not formulate requirements regarding the control of piles and columns made in the ground with the use of such technologies as CFA (continuous flight auger), FDP (full displacement pile), SDC (soil displacement column), Omega piles, columns formed by means of vibroflotation, DSM (deep soil mixing) or jet-grouting (soilcrete). The risk associated with their manufacturing is greater than in the case of traditional technologies (the piles bored in casings or pre-cast concrete piles). The sources of uncertainty are:

- limited control of the formation process,
- limited control of a pile/column material,
- oftentimes, lack of concrete reinforcement,
- sensitivity to the „human factor" – whether or not the contractors are conscious of potential risks.

In general, the quality control of pile and column manufacturing is guaranteed by the acoustic methods of length and continuity investigation, introduced to the engineering practice. Only a few academic centers and contracting companies possess the equipment appropriate for that type of investigation. The idea of such tests, based on the elastic wave (induced by means of a hammer blow), is not complicated, and a series of documented model and field tests in the natural scale was described by Gwizdała [5, 9, 10].

A separate, and a far more complex issue, is the inventory control of foundation piles which are located under the existing structure, when there is no access to the pile heads. Such situations have been frequent recently in transportation engineering: when bridges and viaducts are rebuilt in order to enter a higher load-capacity class, since the inventory of the foundation is indispensable for the appropriate designing of reinforcement.

In the recent years a number of methods have been developed on the basis of seismic sensors arranged in series or moved down in a borehole parallel to the pile under investigation.

It has to be stressed that by means of the above mentioned methods it is also possible to make an inventory of a number of structures by nature submerged in the ground: massive structures, retaining walls, sheet pile walls, diaphragm walls and palisades.

This article presents an overview of non-destructive methods of examining piles, used for the control of their manufacturing, but, above all, their continuity and length evaluation. Also the fundamentals of measurement and result analysis have been included.

2. PILE TESTING METHODS, MEASUREMENT RESULTS AND RULES OF RESULT ANALYSIS

2.1. The PIT and SIT methods

In the tests by means of the SIT (sonic integrity test) and the PIT (pile integrity test), the initiation of measurement consists in the excitation of an elastic wave, using an appropriately calibrated hammer with the tip made of cured resin [12]. Measurement sets for the SIT and the PIT method have been shown in Figures 1 and 2, respectively [18].

Fig. 1. and 2. The SIT [18] and the PIT set for length and continuity evaluation.

The examination of pile continuity is based on the velocity of wave propagation and its reflection in a continuous medium. When the wave encounters the pile’s end, its narrowing or a cracking spot, it reflects off and returns to the pile head surface. That is recorded by the receiver. Subsequently, the test results are worked out with the help of a suitable computer program.

Knowing the time of wave return t, it is possible to calculate pile length L_p from the following equation:

$$L_p = \frac{t}{2 \cdot V_b} \qquad (1)$$

where: V_b is the velocity of the wave propagation in the pile’s concrete

Sample results of tests carried out by means of the PIT method are shown below. Figure 3a presents the result of the analyses made for a 9-meter long continuous pile. Both its length, as well as its continuity, does not raise doubts. The analysis of frequency enclosed below is of quantitative nature but it presents “quite accurately” the inferred pile length. In the case of the

pile presented in Figure 3b it may be suspected that at the depth of about 3.5 m there is a considerable change in the cross-section. That is confirmed on the frequency diagram, where the pile length is estimated as 3.2÷3.7 m. The pile, the examination of which is shown in Fig. 3b, was not driven to the full depth, because the piling hammer operator registered a sudden change in the driving resistance. After the pile was driven to the level of 3.40 m below the pile's head, a transverse cracking could be observed.

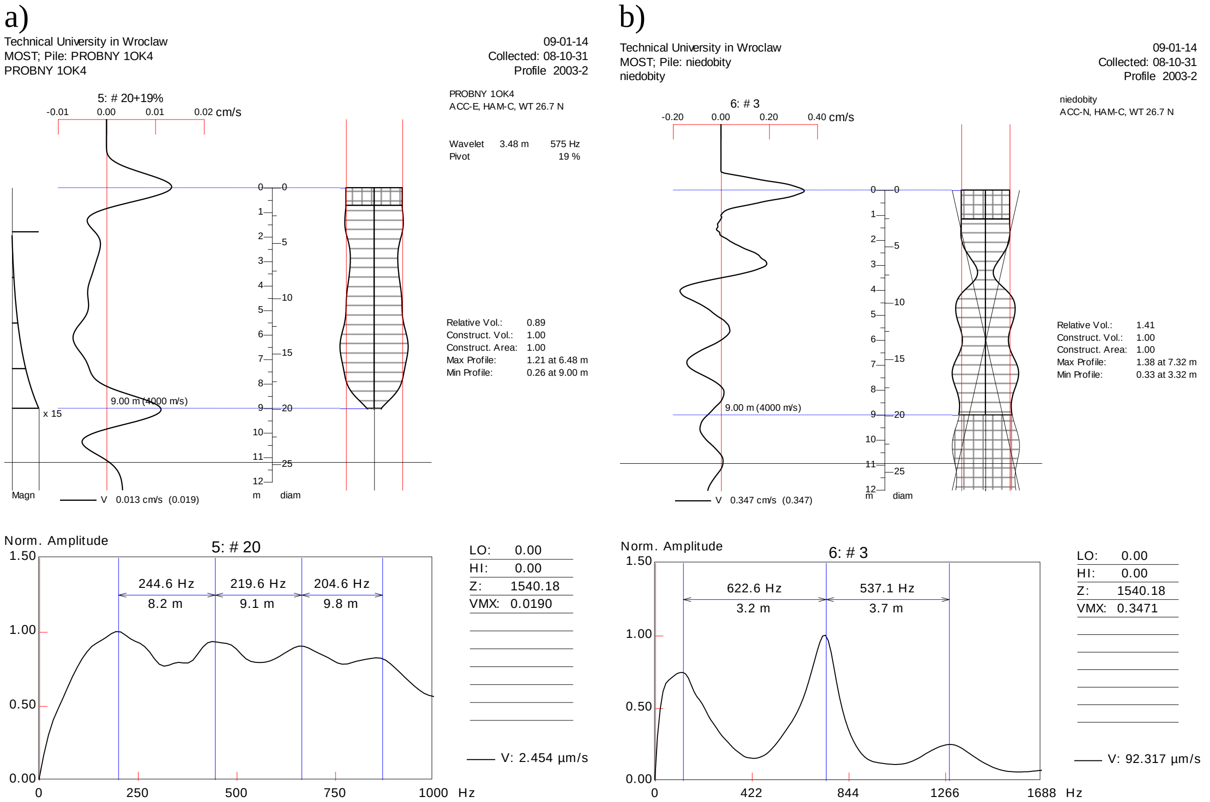

Fig 3. The results of the PIT tests for:

a) a 9.0-meter long, continuous pile, b) a pile with a cracking at the distance of 3.5 m from the pile's head

In the case of pre-cast concrete piles there cannot occur any narrowing, and its length may be measured before it is driven. That is why the above mentioned examination makes it possible to determine whether the pile did not break in course of driving or whether the contractor did not eventually decide to use the piles that were shorter than those initially designed. The issues of calibration of pre-cast concrete pile tests by means of the PIT method, with respect to the appropriate wave velocity determination, have been described in [12]. Experiments show that the velocity of wave propagation in pre-cast concrete piles (concrete B50) equals about 4000 – 4150 m/s, whereas in bored piles, and especially the CFA piles (sand concrete B25 with a fluid consistency), it is smaller and no greater than almost 4000 m/s. Slower wave propagation results from a smaller leak-tightness and lower class of concrete.

An additional factor that has to be taken into account is the time that elapsed from the making of a pile to its examination, since the velocity of an elastic wave in the pile depends on its growing strength. The experience gained by the authors confirms that the testing of piles, before the pile material has achieved its full strength (when the wave velocity value is smaller than the assumed one), may lead to comic mistakes, when the pile length values are

even larger by 10% (at the wave velocity of the order of 3600 m/s) from the values declared by the piling contractor.

It is extremely difficult to interpret the examination of soil-concrete columns that were made by means of injective technologies or the DSM (deep soil mixing) method, as the column material is heterogeneous to the extent that it does not permit to use the implemented mathematical pile model.

2.2. Impulse-Response s'Mash method

In the tests by means of Impulse-Response s'Mash method, the initiation of measurement procedure consists in the excitation of an elastic wave by means of a suitably calibrated hammer with the tip made of rubber [6-8, 11, 14, 15]. The principle of operation of a portable measurement set, consisting of a hammer, geophone and a laptop with specialist software for data processing (Fig. 3) has been presented in detail in publication [14].

The research carried out at Wroclaw Technical University in order to diagnose foundation piles also employs non-destructive Impulse-Response s'Mash method [14]. The equipment set and the way in which tests are performed is shown in Figures 3 and 4. The method is intended mainly for the examination of concrete structures, including massive structures and floors, but it is also well suitable for pile tests.

Fig. 3 and 4. Impulse-Response s'Mash set and the way the test is performed [17]

In the analysis of the results the following parameters are taken into account in the first place: maximum variability P, minimum variability of a flawless pile Q_{max} and minimum variability of a faulty pile Q_{min}. On the basis of those parameters, read from the diagram, the average pile variability is determined, using the following equation:

$$N_{min,max} = \sqrt{P \cdot Q_{min,max}} \tag{2}$$

When there is a fault that consists in a change of the pile cross-sectional area, if the concrete density ρ is known and wave velocity V_b is determined, the following equation should be used in order to estimate pile's cross-sectional area:

$$A_{\min,\max} = \frac{1}{N_{\min,\max} \cdot \rho \cdot V_b} \tag{3}$$

The formula below has to be applied for the purpose of pile length L_p determination:

$$L_p = \frac{V_b}{2 \cdot \Delta f} \tag{4}$$

where: Δf is a substantial frequency range for a flawless pile.

In order to indicate the depth at which some fault is located, equation (4) takes on the shape of the following formula:

$$L_H = \frac{C_p}{2 \cdot \Delta f'} \tag{5}$$

where : *Δf'* is a substantial frequency range for a faulty pile.

The test itself looks as follows: after the pile head has been hit with a suitably calibrated hammer (with a rubber tip), geophone records the signal in order to obtain data. After that, using an appropriate software module, the analysis of the recorded signals is carried out. A sample signal registered by means of Impulse-Response equipment as been shown in Figure 5 and 6.

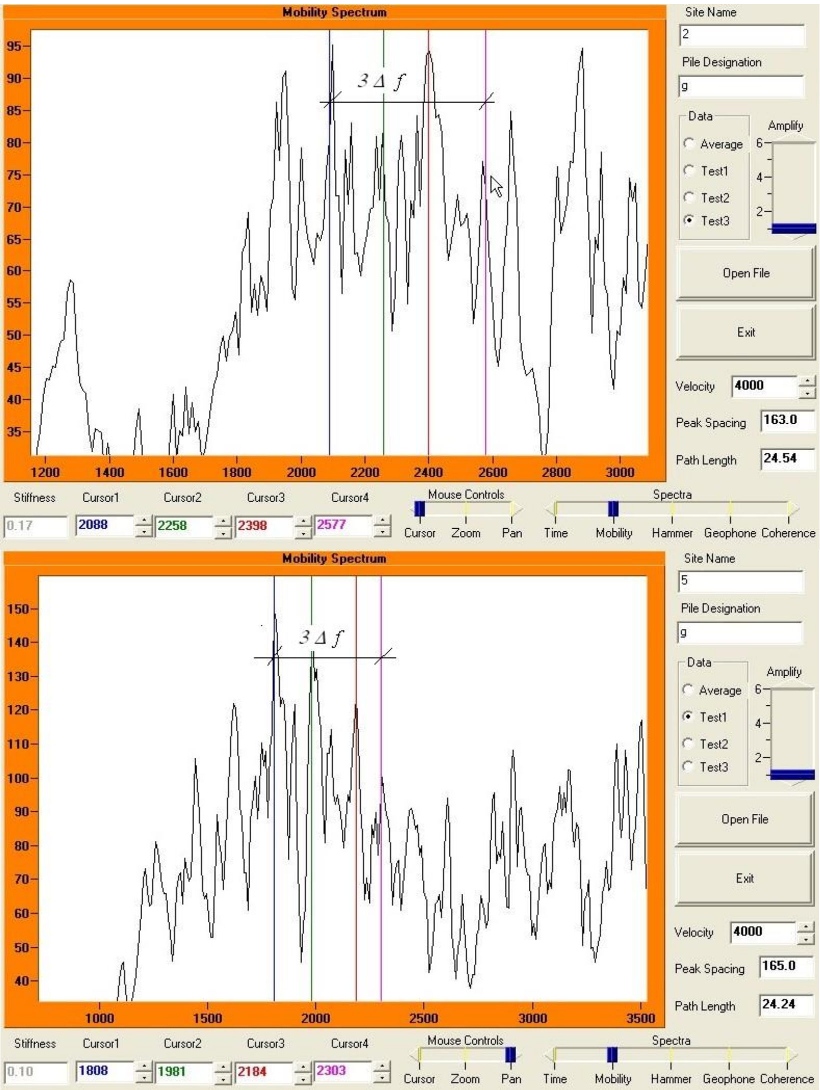

Fig. 5 and 6. A sample signal registered by means of Impulse-Response s'Mash method

2.3. Parallel Seismic Method

In Parallel Seismic Method a borehole is made in the ground alongside the pile; in the borehole a hydrophone is placed. Subsequently, using a calibrated hammer, one has to hit the pile head or the pile capping beam. The PSI (Parallel Seismic Instrument) set by Piletest Ltd [20] and the operation of the PST (Parallel Seismic Test) set by Testconsult [19] has been shown below, in Figures 7 and 8, respectively.

Fig. 7. The PSI set [20]

Fig. 8. Inventory by means of the PST method [17]

The essential advantage of that method seems to be its capability of examining the structures topped by a pile capping beam, i.e. when there is no access to the pile head whatsoever. A significant obstacle, in comparison with the methods described so far, is that the technique requires that a stabilized borehole is made to the depth that is larger than the expected length of the item under inventory. In the borehole the hydrophone is lowered. On the other hand, it is possible to bring together the boring of the hole with soil investigation of the subsequent layers along the pile side surface and below the pile's base, which makes it possible to assess the pile's load capacity.

The diagram of the PST set operation, taken from www.testconsult.co.uk [19], is show in Figure 9, and the interpretation of the PSI pile test – in Figure 10 [20].

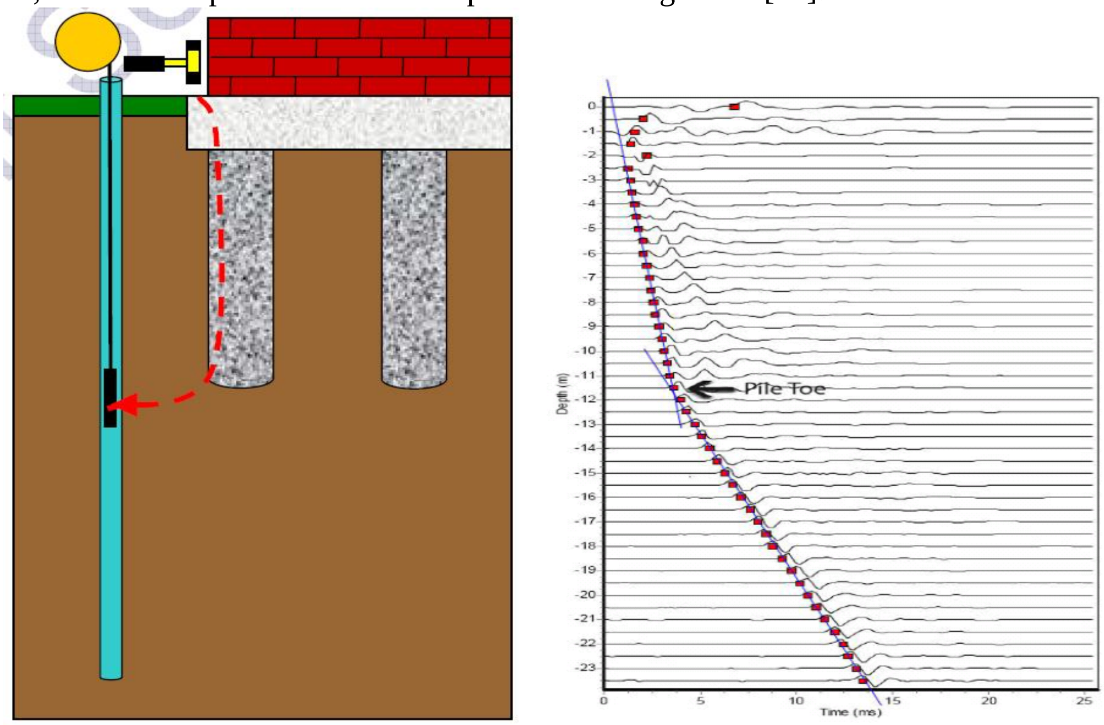

Fig 9. The diagram of Parallel Seismic Testing method's principles of operation [19]

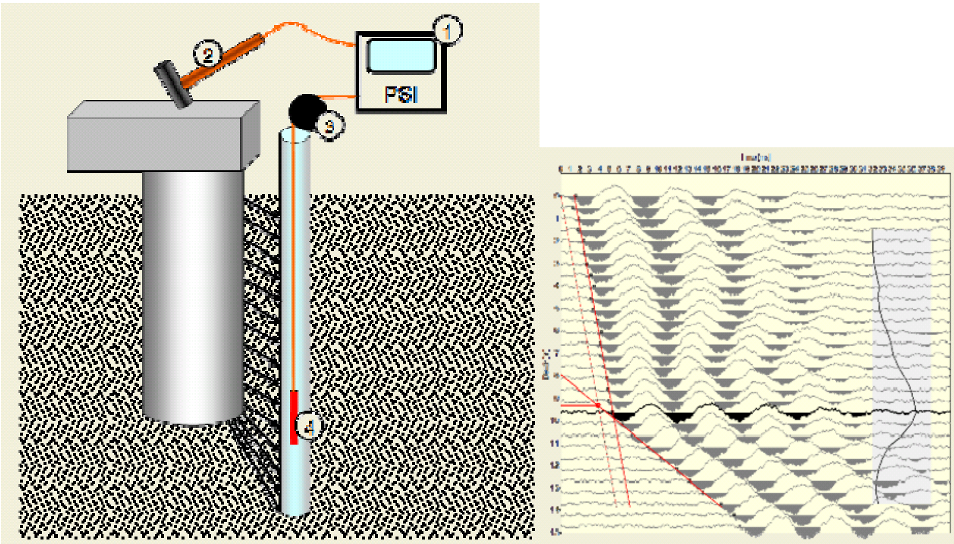

Fig 10. The diagram of Parallel Seismic Instrument operation [20]
1-data reader, 2-calibrated hammer, 3-reel, 4-hydrophone

It has to be stressed that such test enables also the inventory of the length of sheet pile walls or palisades topped by the quay structure. It is especially important when it is necessary to obtain data for further designing of canal deepening or of increasing its upper surcharge (of the quay surface).

3. CONCLUSIONS

The overview of the non-destructive pile investigation methods presented in this work proves that we witness an on-going development of exploratory techniques used for pile quality control, especially from the point of view of their length and continuity. The fundamentals of measurement and result analysis, as well as sample results, included in this overview, show that the tests by means of both the PIT and the SIT method, as well as Impulse-Response s'Mash method, may be successfully applied in non-destructive control of pile manufacturing and in diagnostics of concrete and ferroconcrete piles. In many countries those methods are included in the obliging standardization and carried out routinely as part of pile works control [2].

The tests performed by the authors by means of the PIT and Impulse-Response s'Mash methods confirmed that those techniques make it possible to evaluate in a quick and direct manner the pile's length, its cross-sectional area and a potential change in that area (narrowing, broadening) at the height, but also at the depth, at which that change occurs. In work [14] it has been emphasized that such tests are especially vital when the piles are manufactured using modern technologies of placing the concrete in the ground (CFA piles, Omega piles, columns formed by means of vibroflotation). Also displacement piles should be examined by means of non-destructive methods, since there is always a risk of damaging them in the process of installing a large pile group.

The methods of Parallel Seismic, currently introduced in the world, despite the relative difficulty of the testing itself (due to the necessity of boring a stabilized deep hole), make it possible to diagnose the existing pile foundations and retaining walls submerged in the ground, when there is no access to the pile heads. That proves especially appealing in the case of re-development and modernization of the structures, when it is possible or necessary to take advantage of the elements of their foundations.

The research carried out currently at Wroclaw Technical University aims at establishing uniform criteria of the selection of non-destructive exploratory technologies for a given type of problems. The analysis entails, above all, the issues of relevance of particular testing techniques with respect to pile slenderness ratio (length-to-diameter ratio), the strength of the soil along pile side surfaces (the issue of wave propagation), the velocity of the elastic wave propagation in the piles and columns made by means of modern piling technologies and the change of that velocity in the time needed for the pile or column material to gain its full strength.

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