Interesting Developments in Testing Methods Applied to Foundation Piles

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Abstract. Both: piling technologies and pile testing methods are a subject of current development. New technologies, providing larger diameters or using in-situ materials, are very demanding in terms of providing proper quality of execution of works. That concerns the material quality and continuity which define the integral strength of pile. On the other side we have the capacity of the ground around the pile and its ability to carry the loads transferred by shaft and pile base. Inhomogeneous nature of soils and a relatively small amount of tested piles imposes very good understanding of small amount of results. In some special cases the capacity test itself form an important cost in the piling contract. This work presents a brief description of selected testing methods and authors remarks based on cooperation with Universities constantly developing new ideas. Paper presents some experience based remarks on integrity testing by means of low energy impact (low strain) and introduces selected (Polish) developments in the field of closed-end pipe piles testing based on bi-directional loading, similar to Osterberg idea, but without sacrificial hydraulic jack. Such test is suitable especially when steel piles are used for temporary support in the rivers, where constructing of conventional testing appliance with anchor piles or kentledge meets technical problems. According to the author’s experience, such tests were not yet used on the building site but they bring a real potential especially, when the displacement control can be provided from the river bank using surveying techniques.

1. Introduction – testing the quality of foundation piles and other inspection procedures

The quality testing refers mainly to verifying continuity and length of piles using low stress methods like: Pile Integrity Test (PIT), Sonic Integrity Test (SIT) or Pile Echo Test (PET); not so often the scanning with Cross-hole Sonic Logging (CSL) method or pile survey under the structure is used. A common practice is usually reduced to law strain test which can be performed if only the access to pile head is granted [1]. When there is no access to pile head, other techniques, requiring parallel drilling must be considered.

Another group of tests developing dynamically – especially due to the Eurocodes knocking at the door – are the techniques which enable to analyse the distribution of bearing capacity of the grounds around (along the pile shaft) and in the base of pile, such as application of Osterberg cell [2] or equipping the piles with strain gauges secured to pile reinforcement. Other bidirectional tests were developed in 1988 by Slovak engineers [3] for bored piles and by Hayden [4] for slender piles. These
operations are pioneering nature in Poland, they were not so far widely described nor tested but their value cannot be stressed enough [4]. Recently, new ideas were presented by Baca et al. [6] who developed original idea of Hayden by means of bi-directional steel testing appliance which enables for controlling the capacity of closed-end steel piles [7].

2. Methods of control tests for pile integrity and length

Dynamic development of piling technologies having been observed now brings essential challenges to participants of construction process referring to quality assurance: current inspection of works and also acceptance tests for piles and columns made with new technologies frequently not specified in standards. It especially refers to control of length and continuity of these components. It should be noted that reinforced concrete piles and soil-cement columns belong to rare elements of structures which inspection is very straitened, as (except the head) there is no access in practice. Polish Standard PN-83/B-02482 poses no requirements for inspecting piles and columns made in soil using such technologies as CFA (continuous flight auger), driven piles (FDP – full displacement pile, SDC – soil displacement column), Omega piles, columns formed with immersion vibrator, DSM (deep soil mixing) and jet-grouting (soilerete). The related risk is higher than that in traditional technologies (bored piles in shielding pipes or prefabricated piles).

The factors of uncertainty are here as follows:
- limited control over formation process,
- limited control of pile or column material,
- frequently there is no reinforcement,
- sensitivity to “human factor” – awareness of threats from contractors.

In general, the quality control of pile and column execution is ensured by acoustic methods, introduced to engineering practice, for testing their length and continuity. Appropriate instrumentation is at disposal of some academic centres and contracting companies. The idea of these examinations is based on analysing the elastic wave in the pile (caused by hammer hit) [1], [9].

A separate and much more complex problem is the inspection or survey of foundation piles which are located under existing structure when pile heads are inaccessible. Such cases are quite often lately in highway and railway structures: alterations of bridges and overpasses to higher class of loads, when foundation survey is necessary to ensure proper design of reinforcement.

A number of method based on application of seismic sensors, arranged in series or moved along a hole parallel to the pile being surveyed, have been developed in recent years. It shall be stressed that such methods can be also used to survey earth-sheltered massive structures and retaining walls, sheet pilings, diaphragm walls and palisades. Below, there is a review of destructive testing of piles used to verify their quality of the workmanship – examining their length and continuity. Also the basis of measurements and rules for result analysis are presented.

2.1. PIT and SIT methods

In testing methods SIT (sonic integrity test) and PIT (pile integrity test) the measurement is initiated by inducing an elastic wave using appropriated calibrated hammer with end made out of hardened resin. Measurement kits for SIT and PIT methods are shown in Fig. 1 and Fig.2, respectively. The continuity test is based on wave propagation velocity and wave reflection in continuous media. The wave, while meeting the pile end, its contraction or fracture, reflects and returns to the head surface. This is recorded by the receiver. Then, using computer software, the testing results are prepared. When wave return time \( t \) is known, the pile length \( L_p \) can be calculated from the formula (1):

\[
L_p = \frac{t}{2} V_b
\]

where: \( V_b \) is the wave velocity in pile concrete.
To keep the result reliable, it is recommended that the pile slenderness (i.e. its length to diameter ratio) would not exceed 30. However, measurements were also taken for piles in weak soils where slenderness was 60.

**Figure 1.** Pile Integrity Test (PIT equipment of METRIS) for examining pile length and continuity

a) driven pile,  

b) CFA pile

There are numerous papers about experiences with such low strain testing. In general, authors pay a major attention to testing methodology for various piling technologies [10]. Above, there are exemplary results of examinations with PIT method, made by Technical University in Wroclaw for driven piles made by AARSLEFF. Figure 2a gives the result of analyses made for continuous pile 9.0 m long. There are no doubts about its length and continuity. The analysis given below is of qualitative nature; however, it “quite precisely” shows the interpreted length of pile. In case of pile which examination is shown in Fig. 2b, an essential change in its cross-section at the depth of about 3.5 m can be suspected. This is confirmed in frequency diagram where the pile length was estimated at 3.2 to 3.7 m. The pile which examination is presented in Fig. 2b was not driven to the full depth because the operator of pile driver notices a sudden change of driving resistance. Following the pile was unearthed to 3.40 m below pile head, a transverse fracture was revealed.

In case of prefabricated piles, pile contraction is not possible, and pile length can be determined prior it is driven. Hence, this testing is used to determine whether given pile was not broken during driving it and whether the contractor did not use shorter piles than those given in documentation.
issues of testing calibration for prefabri cation piles examined with PIT method in terms of proper determination of wave velocity in pile was described in [12]. Experience proved that wave propagation velocity in prefabricated piles (C40/50 concrete) is about 4.150 m/s. The velocity in bored piles (C20/25 concrete), and especially in CFA piles (C20/25 sand concrete with liquid consistence) is lower and amounts to less than 4.000 m/s. Lower velocity of wave propagation is related to lower integrity and lower class of concrete [13].

The time elapsed from completing the pile to its examination is an additional factor which needs to be taken into account. It is because the velocity of elastic wave propagation is dependent on incremental strength of the pile. That issue was recently widely described by numerous authors [14][15]. In general, it is recommended not to make examinations earlier than 7 days after pile completion (pouring the concrete). According to author’s experience from large number of tests performed by METRIS company, testing piles prior the pile medium reaches its full strength (when wave velocity is less than assumed one) is possible, however can lead to funny mistakes when, at wave velocity about 3600 m/s, the pile length is found to be even 10% longer than that declared by pile work contractor. A series of testing made after 5-12 days after completing the concrete columns indicated that wave velocities in C20/25 concrete were from 3250 to 3600 m/s approximately. Those values are in general in accordance with recommendations given by Rybak [16]. Extremely difficult for interpreting is testing of soil-cement columns made with injection technologies or with deep soil mixing method (DSM). The column material is here so heterogeneous (see Figure 3) that we cannot use implemented mathematical model of the pile. Quality testing is of special importance in case of technologies susceptible for unpredictable conditions in the subbase and “human factor”. Finally, even in the case of concrete piles, we should not expect an accuracy exceeding 5-10%. The variability of PEM test results (Pile Echo Method) was also described by Amir [17].

2.2. CSL method (cross-hole sonic logging)

The CSL method requires protection of the holes over the full pile length; inside them the wave transmitter and receiver are moving. Hence, the method can be used provided the pile is appropriately prepared during its execution. It considerably reduces the random nature of testing. It should be stressed that CSL testing allows for controlling the piles of unlimited length.

2.3. Examining the pile material – core drilling

A progress in development of pile technologies is also related to more and more common use of soil improvement technologies by its deep mixing with cement paste. Depending on soil grade and mixing method (mechanical like DSM or CSM or high-pressure like jet-grouting) generated are media of much diversified strength parameters. What need to be emphasized, the compression strength alone is not the sole criterion because, for instance, jet-grouted columns made in gravels featuring relatively high strength (C25/30) are at the same time very porous, which may limit the durability of reinforcement sunk in them.

Figure 3. Core samples from heads of prefabricated driven piles (left) and DSM columns (right)
A typical examination of the pile or column material is the compression test made on core samples. An important issue is that the samples should be taken from the whole volume of executed pile or column and not only from their axis where they, to the most degree, represent the strength of the injected binder. Another problem refers to testing for material strength in prefabricated piles. Obviously, the subject of testing is not the strength of concrete in the prefabricated pile at the fabrication plant, as this is the care of manufacturer (usually C40/50), but the strength of pile after it was driven in terms of possible fractures during transportation and driving. Examinations were made at Wroclaw University of Technology on core samples cut out of pile heads (about 30 cm from the head) manifested that concrete strength determined on standard samples was C40/50-C50/60. No fractures in samples were found which would accelerate their failure in testing machine.

2.4. Length inspection - Parallel Seismic Method
The Parallel Seismic method consists in preparing a hole in soil along the pile where a hydrophone is placed. Then, using a calibrated hammer a hit is made either to pile head or to top plate of pile group. The PSI kit (Parallel Seismic Instrument) acc. to Piletest Ltd [18] and the PST kit (Parallel Seismic Test) made by Testconsult Cиноабт can be found in common practice [18].

The most important advantage of this method seems the possibility of examining the structures crowned with a top plate, i.e. when the pile head is inaccessible. However, when comparing with the methods presented above, a big impediment is the necessity to make stabilized hole deeper than the expected length of the component under survey. A hydrophone is then moved down the hole. Executing this hole can be connected with geotechnical examinations of the subbase in successive layers along the pile shaft and beneath the base of the pile being under survey which could then be used to conclude about its load bearing capacity. The interpretation of PSI (Piletest) testing is given in figure 4 [18], while scheme of PST kit operation, taken from the website www.testconsult.co.uk [18], is shown in figure 5.

It is worth noting that such testing allows also for surveying the length of sheet pilings or palisades crowned with embankment structure. It is of special importance when we need data to make stability calculations in terms of dredging a channel or enlarging the top load of surcharge (embankment surface).
3. Examinations with Osterberg cell (O-cell) and new similar ideas

While analysing the bearing capacity of test loaded piles, when the examinations are to serve not only to show the margin of test-loaded pile capacity, it is important to separate the capacity of the base and that of the pile shaft. The solution for executing such examination, technically simple however expensive, is to use an actuator located in the pile base (base load cell). Measurement of the force and lifting the pile head, while simultaneously measuring the force applied in its base, allows to get information about pile bearing capacity and, at the same time, about the bearing capacity distribution to pile base and shaft. The actuator is lost and the cell space subjects to injection. Detailed description of the method and the rules of analysing the results are provided in papers [2], [20]. A comprehensive summary (state of the art) of bi-directional testing was given by England in the works [21].

Figure 5. Functional diagram of Parallel Seismic Testing method by Testconsult [18].

Figure 6. Actuators secured to pile reinforcement by foundation-alliance [23]
Various methods of test data examination are proposed in work of England [21]. Other authors developed the methods of equivalent load-settlement curve derived on the basis of bi-directional test [23]. As it was previously mentioned, among all the advantages, the Osterberg test has one major problem – the hydraulic jacks are sacrificial. The problem may be solved by shifting it to the pile head and transmitting the force through the piston in the pile vertical axis. Such test require however a reliable instrumentation for displacement measurements. When the instrumentation is expected to be removable too, the case becomes even more complicated. Interesting development was recently published by Baca et al. [6] who examined various surveying techniques (including laser scanning) for displacement control of “piston-test” which resembles original Hayden [4] and VUIS [3] ideas adopted for closed end pipe piles.

If the bi-directional test can be combined with standard pile head loading against a reaction frame, the separation of pile base and pile shaft capacity can be derived. Such sequence of testing was also reported by Baca et al. [25], who tested the possibility and conditions of cyclic loading of pile toe in various shaft load conditions.

4. Summary and conclusions
Various inspection techniques provide a possibility of quality and capacity testing of piles. Experiences suggest that sometimes we can attempt to interpret the results of quality testing for piles with small age or pretty large slenderness, i.e. the factors for which caution is advised with conclusions. In general, it should be stated that modern testing technologies create temptation of over interpreting the testing results. Creating a data base including test load results for piles, at least those which are at the disposal of testing companies and/or academic centres, seems to be a valuable initiative. Such base would enable to specify local (national) correlations between static and dynamic testing for various grades of soil and piling technologies. It is of special importance at the time of introducing the Eurocode 7, which admits (and even prefers) pile designing on the basis of results from various test loads. Data bases are in practice the sole reliable source of information for creating respective national appendices or standards for pile engineering.

There is a big field of possible cooperation between testing companies, who gather test data and develop the technologies and Universities, where those data should be post-processed with respect to soil conditions, materials and loading sequence. Those data should also be a subject of exchange because larger statistic probes can guarantee a synergy of accuracy and lower standard deviations of estimated results. The authors, representing both sides (contractor/university) are willing to emphasize one more issue. The research based on real test results will never lead to scientifically correct but purely nonsense statements, which have no value in contemporary building practice.

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