Ultrasonic Integrity Testing for Bored Piles - A Challenge

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Abstract

In recent years, the application of non-destructive testing in the field of special geotechnical works has grown. In particular for bored piles, clients specify ultrasonic integrity testing on a much more frequent basis. Bored piles are executed by specialist contractors, in compliance with established technical standards. For preparation of ultrasonic integrity testing, pipes are installed on the reinforcement cage. After placement, setting and hardening of the concrete, the ultrasonic testing can be carried out. Within the last decade, Bauer has experienced several such applications on construction sites worldwide. Key findings such as typical sources of mistakes during installation, testing, and evaluation are presented. A practical approach assists in classifying anomalies and shares responsibilities between contractual partners. It takes into account the fact that minor deviations from an absolute ‘perfect product’ must generally be accepted within an industrial production of bored piles in natural ground.

Quality assurance and management of the processes prior and parallel to the actual execution are to be preferred. Incoming material inspection, setting, checking and verifying limit values, detailed records and written approvals should be relied upon to a greater extent than post-construction quality control. Possible anomalies should never be assessed on the results of ultrasonic testing only.

Keywords: Ultrasonic, Integrity, Bored Pile

1. Execution and standard quality control of bored piles

Specialist deep foundation contractors produce bored piles in accordance with established technical standards. EN 1536:2010 [1] has been developed by European experts over the last decades and comprises approved regulations for execution of bored piles. In CEN member countries, national appendices may specify additional clauses to the basic code where necessary. In addition, the Recommendations on Piling (EA-Pfähle) [2] contain best practice rules and may give helpful supplementary information for designers, consultants and contractors.

After excavation, and cleaning of the pile base and cleaning or exchange of the supporting fluid, the reinforcement cage is installed, together with the testing pipes where ultrasonic testing has been specified, and prior to concreting.

Concrete placement under submerged conditions is shown in Figure 1. Fresh concrete must be able to easily displace already placed concrete and any supporting fluid, without mixing. Therefore, the concrete has to be of good flowability and have sufficient cohesion. In order to achieve full embedment and sufficient cover to the reinforcement bars, minimum clear distances and concrete cover as well as maximum grain size of the aggregate must be considered at the design stage. Usually, for large bored piles, minimum design cover is 75 mm and clear distance of longitudinal bars must not be below ¼ of the coarse aggregate size [1].
The concrete flow patterns inside a reinforced bored pile are specific and reflect the conditions of both tremie placement process and resistances to flow by any surfaces within the excavation, as shown in Figure 1. It is well known that these factors give rise to an uneven concrete velocity profile whereby the rising concrete displaces already poured concrete to the sides of the shaft. Different concrete loads will be positioned next to each other, over the height of the pile [3].

![Figure 1: Concrete placement under submerged conditions, schematically, and in detail](image)

2. Ultrasonic test method for quality control in bored piles

The Ultrasonic Test Method

The principle of ultrasonic testing has been applied for quality control of deep excavation for diaphragm walls for decades for verification of verticality and to establish the actual dimensions of the trench before concreting. Although the sensitivity of the sensor is well known and often causes some difficulties in achieving reasonable results, the lack of a better solution has led to the method becoming well accepted and used worldwide where excavations must be supported by a fluid. In order to improve the actual state-of-the-art, Bauer has developed the Bauer Sonic Meter “BSM 250” which, amongst many other features self-calibrates over depth and thus gives more reliable results.

In order to test the integrity of a completed bored pile, the ultrasonic signal of compression waves is analyzed between two parallel pipes, as shown in Figure 2.
Deviations from the concrete’s continuity or homogeneity – in a decimeter scale – are detected by relevant changes in velocity or energy absorption of transmitted waves, as shown in Figure 3.

Figure 2: Setting for the ultrasonic integrity testing of a bored pile.

Figure 3: Ultrasonic measurement result. First arrival time and energy derived from waterfall graph origin.
**Preparation and execution of ultrasonic testing of bored piles**

Special pipes must be installed on the reinforcement cage. Typically, four pipes are used, allowing six paths to be tested within the cross section – inside the cage. Additional pipes may be installed as a substitute in case of loss of a pipe for whatever reason. The number and the position of the pipes should be recorded on the drawings. In no instance should the pipes be allowed to reduce the clear distances required for concrete flow. Since the initiation of the concrete pour is often critical to the quality of the whole placement it is recommended to curtail the pipes 50 cm above the base of the excavation.

If the cage is installed in sections the pipes in the upper section must be vertically moveable for coupling. But, the pipes shall be fixed in a manner where no lateral movement is allowed during cage installation and concrete placement. If an evaluation of the wave velocity is required, the actual (horizontal) distances between pipes should be recorded.

Pipes must be watertight at their base and joints. A reduction in the inner diameter must be avoided, an additional sealing over the joints may affect the ultrasonic signal. Therefore, the position of the joints should also be recorded. Steel pipes with welded caps and crimped connections have proved effective (see Figure 4).

![Figure 4: Example of a steel pipe with connection and end cap](image)

Pipes must be filled with water when being lowered into the excavation filled with supporting fluid in order to minimize floating forces. Before concreting the pipes must be closed at their top. After concreting, and before testing, the following steps are recommended:

- Cutting the testing pipes to the same top elevation
- Measuring and recording of the actual distances between pipes at the accessible top of the pile
- Checking the continuity of the pipes by using a dummy probe
- If necessary, cleaning the pipes by use of a weighted brush
- Measuring and recording the maximum depth of each pipe
- Refilling of the pipes with water
- Closing the pipes until testing is commenced
The shallowest depth determines the lower reference elevation. The upper reference elevation shall be the design cut-off level of the pile. The determination of the actual testing time must obey two contradictory requirements: the concrete must be sufficiently hardened, hence testing cannot be performed in very young concrete; and the construction works should not be restricted, hence the testing shall be performed, and evaluated as soon as possible. Until then, the pipes must be protected against damage at all times.

The testing commences after lowering both probes to the designated lower reference elevation. The probes are slowly pulled upwards with a rope system. The same elevation of the probes must be verified frequently and any deviations recorded. The technical measurement regulations should follow the relevant standards (e.g., ASTM D6760-02 (USA) or NF P94-160-1 (France)).

In suspicious areas repeated or additional measurements should be carried out. If required, a tomographic analysis is possible by controlled height variation of the probes, as shown in Figure 5.

![Figure 5: Display of tomographic ultrasonic measurements](image)

In most cases, it is sufficient to undertake theoretical considerations to investigate the size of any possible anomaly within the pile’s cross-section. The average pulse velocity from the area above and below the critical section must be calculated, taking into account all available paths. Using this characteristic value $v_{P,\text{concrete}}$ as a reference for the sound concrete, and then applying the measured First Arrival Time (FAT) and the known (or assessed) distance of the suspicious path, a specific graph can be set up. From this graph, a probable length of the possible inclusion, filled with a certain material, can be assessed. A guideline from the U.S. American Federal Highway Administration [4] gives reference values for various materials like clay or sand, even for a de-bonded testing pipe (see Figure 6).
Reliability of the ultrasonic test in bored piles

For assessing the reliability, systematic and accidental influences on the testing should be distinguished. In general, testing is relevant for piles of 1.2 m diameter or greater. This allows both a sufficient path length to detect significant changes in pulse velocity and a test area inside the reinforcement cage of at least 50% of the total cross section.

The cover section outside the reinforcement cage and outside the testing pipes, in particular controlling the durability of the structural element, cannot be ultrasonic tested in a single pile. In secant pile walls the ultrasonic waves may be transmitted between pipes in adjacent piles. Due to the sensitivity of the ultrasonic testing on inclusions of non-concrete materials, which will always be present in the joints of bored piles, an expert opinion is needed for quality assessment. Yet, this variation of ultrasonic integrity testing appears questionable due to likely misinterpretation [5].

Random errors in ultrasonic testing can be recognized and minimized by repeating the testing:

- Lateral space for moving of the probe inside the testing pipes - result can vary by 5%.
- Different elevations of the probes - result can vary by 2% with 20 cm deviation in height.

Systematic influences must be recognised for compensation purposes. The testing pipes are rarely absolutely straight and parallel to each other, and their distances not the same as in the drawings. Pulse velocities calculated from first arrival times and assumed associated distances may therefore become unreliable. The required assessment of the continuity of the concrete is normally determined using the directly measured First Arrival Times, at least in the first assessment.

It is more difficult to assess the influence of other errors such as de-bonding of the pipes, in particular at the connections. An indication for this would be if poor ultrasonic results were repeatedly observed in these sections.
A major influence may be the concrete itself, which can cause significant changes in the pulse velocity by:

- different maturity of concrete at the time of testing, see Figure 7
- different composition of concrete, in particular different coarse aggregate content, see Figure 8.

Figure 7: Examples of the sensitivity of hardening concrete on ultrasonic testing [6]

Figure 8: Influence of strength on ultrasonic velocity, for paste, mortar and concrete composition [7]
The maturity of subsequent batches poured will equalize with time and only have a small influence after several days but can be easily in the range of a few percent for young concrete. But the variation in composition will remain. One reason is, that the flow pattern within a bored pile will allow different batches of concrete to be placed next to each other, at the same elevation. Another reason is, that even concrete from the same load can vary in its composition after placement, until initial set. Even if these variations occur within an acceptable range of concrete quality, they will lead to deviations in pulse velocity.

Some segregation of fresh tremie concrete cannot be avoided due its contradictory demands for good workability, and the settlement of coarse aggregate alone can cause a difference in pulse velocity of up to 20%. Also the fact that tremie concrete may show some bleeding is usually not considered. Even if concrete has been designed for low bleed, some bleeding channels can occur under practical conditions and will influence the ultrasonic testing result. For the same reason locally increased porosity can have a significant impact on pulse velocities. In general, influences should have a similar effect on the pulse velocity as on the elastic modulus without reducing the relevant compressive strength to the same extent.

3. Interpretation of ultrasonic test results and assessment of anomalies

For reasons given above the assessment of pile integrity based solely on ultrasonic analyses is considered unreliable. Minor but acceptable variations in concrete quality and small inclusions will inevitably happen even if design and execution have been conducted with the utmost care. Possible anomalies can be found with ultrasonic testing but these cannot be distinguished from other influences. This is probably the reason why there are no clear and unanimous recommendations on how to assess ultrasonic test results. In the “Drilled Shaft Manual” of the U.S. American Federal Highway Administration [8] classes of concrete quality are addressed. Reflecting the above considerations the concrete quality must not be rated “poor/defect” if FAT is increased by more than 20 % and energy reduction by more than 9 dB, without checking on further indications. In the case of an assumed anomaly all available information on quality control must be cross-checked, in particular the execution records. Subsequently and before consideration of further measures, the possible anomaly should be investigated and rated in terms of its structural relevance. The Recommendations on Piling (EA-Pfähle) [2] present helpful advice for qualitative, and quantatative analyses of anomalies, with regard to the ultrasonic pulse signals.

A case study illustrating the sensitivity of the ultrasonic testing method is given below.

For the currently ongoing construction of the Kingdom Tower in Jeddah, Bauer executed 270 bored piles of 1.5 and 1.8 m diameters with depths from 49 to 109 m, in challenging ground conditions [9]. For the assessment of pile integrity, amongst others, ultrasonic testing of each single pile was a contractual requirement. Initially, results were classified as anomalies where the criteria were not met: an increase in FAT by more than 20 % and energy reduction by more than 9 dB. A defect was assumed if these criteria were found in more than only one ultrasonic path of that particular section. In following evaluations, an anomaly was only rated an imperfection if its dimension was greater than 250 mm. A corresponding inclusion would be less than 3% of the cross section of a 1.5 m diameter pile.

Figure 9 shows a tomographic analysis of a pile section that was rated “poor/defect” in the first instance. It should have had an anomaly at an elevation of 1.0 to 2.3 m below cut-off level (= 0). Deviations in calculated pulse velocities over the pile’s height and cross section are obvious of 40 % and above. Consequently, in particular the area of the suspected anomaly had to be initially rated as a defect. It was agreed to take cores from the areas with assumed
defects. The visual inspection and laboratory test results on the cores proved a quality well above the acceptance criteria for strength, permeability and durability. The main criticism of the tomographic analysis is that pulse velocities need exact travel distances and travel times, but distances are often imprecise, despite careful execution. Therefore, acceptance criteria should preferably be related to the first arrival time FAT, and to energy absorption if needed.

Even using directly evaluated first arrival times, misinterpretations occurred. An area with an increase in FAT by up to 44% was interpreted as a large inclusion, or major defect. Compressive strength results from cores were 82, 85 and 89 MPa and thus far above the required value of 51 MPa. For another pile, the ultrasonic testing showed local deviations of 40% but the cores again had sufficient strengths of 63, 77 and 81 MPa. By visual inspection, the concrete from all drilled cores was classified homogeneous and even the laboratory tests for chloride diffusion gave excellent results. The measured energy reduction in all cases above was below 9 dB, which casts doubt on the initial classification in any event, as described in reference [8]. In piles where both criteria were fulfilled at the same time, ie an increase in FAT of 21 to 37%, and a decrease in energy from 9.2 to 13.3 dB, the evaluated dimensions of possible inclusions with water saturated sand were not above 3 to 5 cm and therefore negligible.

In the section of the pile head pulse signals were significantly attenuated. However, when breaking and chipping down to the cut-off level, no defects or inclusions were found. When concrete slices were split off the pile head even fracture surfaces with evenly distributed coarse aggregates were observed, indicating a high quality and homogeneity of the concrete, as shown in Figure 10.
Eventually, based on the detailed quality records, despite inconsistent and contradictory results from ultrasonic testing, all 270 piles were approved having a high quality, compliant with the technical execution standards in place.

4. Conclusions and Proposal of Contractual Agreements

All stakeholders should accept that ultrasonic integrity testing should only be used as a part of quality control. An assessment of concrete quality, based solely on ultrasonic testing often results is misinterpretation.

The indirect ultrasonic test method gives results only after the piles are constructed. Many errors during preparation, actual measurement and evaluation are possible. Combined with minor acceptable variations in concrete composition and quality, the method becomes very sensitive in contrast to a relatively ‘rough’ pile construction in natural ground conditions. Over decades, basic rules for the execution of bored piles have been established and incorporated into present norms and standards [1] which are continuously updated. Common recommendations of the EFFC and DFI [10] on tremie concrete for deep foundations emphasize that sufficient clear distances of the reinforcement bars and a sufficiently large concrete cover must be considered at the design stage. The main focus of this guideline is to give advice on the correct workability during placement. Both preconditions are essential to allow an experienced and highly skilled concreting team to cast a pile of good quality. These works of course are done in accordance with the relevant standards, and will be recorded using standardized templates.

If ultrasonic testing should apply as a supplementary quality control, the pile production must not be affected. As a matter of course, the provisions on clear space to allow easy concrete flow must be obeyed. To avoid additional resistance during the sensitive situation of initiation of the concrete pour, it is strongly recommended not to have pipes in the lower half meter of the excavation. The alignment of the pipes, preferably made from steel, should be straight and
parallel which demands great care as this is critical for the proper determination of pulse velocities (if needed). The utmost care shall be given to watertight connections of segmental pipes and the recording of their elevations within the pile. Each discontinuity will impact negatively on the results and give rise to false interpretations.

Due to the high sensitivity of ultrasonic testing in bored piles with process related inevitable deviations from a perfect state, further investigations on anomalies in pile sections should only be conducted in relation to “sound” concrete below and above the critical section when:

- the first arrival time (FAT) is increased by more than 20%, and
- the energy reduction is more than 9 dB, and
- the height of the assumed anomaly is present over more than 20 cm, and
- at least 50 % of the measured paths within the section are affected, and
- the assumed inclusion is at least 20 % of the suspicious path’s length.

It is recommended that contractual agreements are based on the above acceptance criteria. Furthermore, it should be determined who is responsible for each stage of the process (installation, measurement and evaluation). The procedure and responsibility in the event of possible anomalies should be agreed in advance. If an anomaly is found, based on the criteria given above, the first action should be to carefully study the quality related documents and other records to check for unusual or irregular occurrences during construction. With no such indications the client or contractor should be responsible for any repeat measurements. With repetition of measurements tomographic investigations should be performed. If the assumption of an anomaly is confirmed for more than 10 % of the related cross section, the structural designer should check if the anomaly is critical at the depth in question, with regard to serviceability and bearing capacity. If it is critical, drill cores should be taken and a camera survey could be performed to verify the dimensions. If these additional investigations show a defect the pile shall be repaired normally at the expense of the contractor. In case of sufficient concrete quality or if the anomaly is only limited to an uncritical extent, the client shall take over responsibility. This proposal of sharing various duties and costs should address the responsibilities of both parties to carefully plan and execute ultrasonic testing. What should be avoided at all costs are unnecessary remedial works based on unsound assumptions and incorrect interpretation of ultrasonic test results.

References


