

Single-Tube Ultrasonic Testing of Pile Integrity¹

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Abstract

It is now universally acknowledged that in bored piles (drilled shafts, caissons) flaws can, and therefore will, occur. The majority of the important flaws can be detected by standard non-destructive testing methods. There are situations, however, when none of these methods is viable. One example is that of small diameter piles, penetrating through rockfill with large cavities and then socketed into rock. The Israel Ministry of Construction and Housing initiated a research project to evaluate the applicability of single hole ultrasonic testing (SHUT) to such piles. The following parameters were to be investigated: Minimum age of concrete that enables testing, the most suitable tube material, tube diameter and most advantageous probe spacing. The goal of this work was to establish the performance envelope of the method and propose a suitable specification for the test procedure.

A suitable test site was selected in Ma'ale Modi'in, Israel, where the subsoil consists of weathered hard dolomite with hard clay pockets. Altogether ten piles were tested, of which eight contained known defects. All testing was performed using the CHUM system manufactured by Piletest.com Ltd. The results prove that SHUT is a very suitable means for integrity testing of small-diameter piles, and may also serve as a clean alternative to radioactive testing of large-diameter piles.

Introduction

Small diameter, percussion-drilled piling, is the preferred foundation method for rocky sites throughout Israel (Amir 1981, Amir 1986). Thanks to the high utilization of concrete strength (a 350 mm pile will carry up to 1.2 MN) and to the speed of construction, such piles are economically very attractive (Amir 1983, Amir 1986). On the other hand, the construction of these piles, as of piles in general, is an invisible process in which the existence of flaws is an unavoidable risk. Fleming et al. (1992) present different reasons for the occurrence of flaws: The use of concrete that is too dry, water penetration into the borehole, collapse in soft strata, falling of boring spoils from the surface, tightly-spaced rebars etc. In small diameter piles, dry chunks of concrete may also get jammed in the reinforcement cage, creating large air-filled voids. Flaws may also develop after the piles have been cast: the use of explosives for nearby excavation and careless trimming of the pile heads are two common causes. At the same time, it is impossible to visually inspect the final product of this risky operation in the same way one inspects a beam or a column. Under such condition, the engineer must

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use indirect (non-destructive imaging) methods for verifying the integrity of the piles. Modern piling specifications (ICE 1996), aware of the subject's importance, include special provisions for such tests.

Definitions

When discussing pile integrity, it is important to distinguish between three terms that are often confused:

An *anomaly* is any irregular feature in the NDT graphic results. An anomaly may be due to the testing instrument (such as noise), to the means used (access tube debonding in a cross-hole test), to the surrounding soil (abrupt changes of soil friction in the sonic test) or to the pile proper. It is the responsibility of the testing laboratory to gather and analyze all relevant data and try to resolve every anomaly before it is declared a flaw.

A *flaw* is any deviation from the planned shape and/or material of the pile.

A *defect* is a flaw that, because of either size or location, may detract from the pile's capacity or durability. The geotechnical engineer and the structural engineer are jointly responsible to decide which flaw comprises a defect.

Integrity testing of piles - standard methods

During the last three decades, several non-destructive methods for pile integrity testing have been suggested (Turner 1997). Among these methods, only two have become standard: Pile echo testing (PET) and the cross-hole ultrasonic method (CHUM). In addition, the radioactive method is still sporadically practiced.

Pulse echo testing (PET)

Pulse echo testing (van Koten and Middendrp 1980) is the most common method for testing the integrity of piles of all kinds. Lately, it was normalized in a widely accepted standard (ASTM 1996). The method consists of hitting the pile head with plastic handheld hammer and recording the reflected waves. From the results, presented in the form of a reflectogram, one can determine the effective length and the continuity of the pile.

Pulse echo testing is very useful, but on the other hand suffers from severe limitations, especially where the pile is socketed into rock after passing through a thick layer of rockfill. In such a case, the upper part of the pile assumes a rough profile that produces "parasitic" reflections. This kind of noise may mask any useful information arriving from below. Moreover, the skin friction in the rock socket itself causes the wave to lose energy until it becomes impossible to separate between signal and noise.

The cross-hole ultrasonic method (CHUM)

The Cross-hole Ultrasonic Method is another standard method (AFNOR 1993). It requires the installation of at least two 50-mm diameter tubes in the piles during casting. The tubes are filled with water to achieve good coupling, and the test is performed after the concrete has hardened sufficiently. An ultrasonic (~50 kHz) transmitter is lowered in one tube, and a compatible receiver in the other one. Both transducers are connected by cables, running through a depth-meter, to the instrument in which the depth, arrival time and energy for every pulse are continuously recorded (Figure 1). As long as the first arrival time (FAT) and the energy are approximately constant, one may conclude that

the concrete between the tubes is uniform and flaw-free. A marked delay in the FAT and/or a marked drop in energy indicate an inferior concrete or an inclusion of foreign material. The wavelength utilized (80 mm in good concrete) provides excellent resolution.

Since the method requires the installation of at least two tubes in a given pile, it is too expensive, impractical and almost ineffective for small diameter piles.

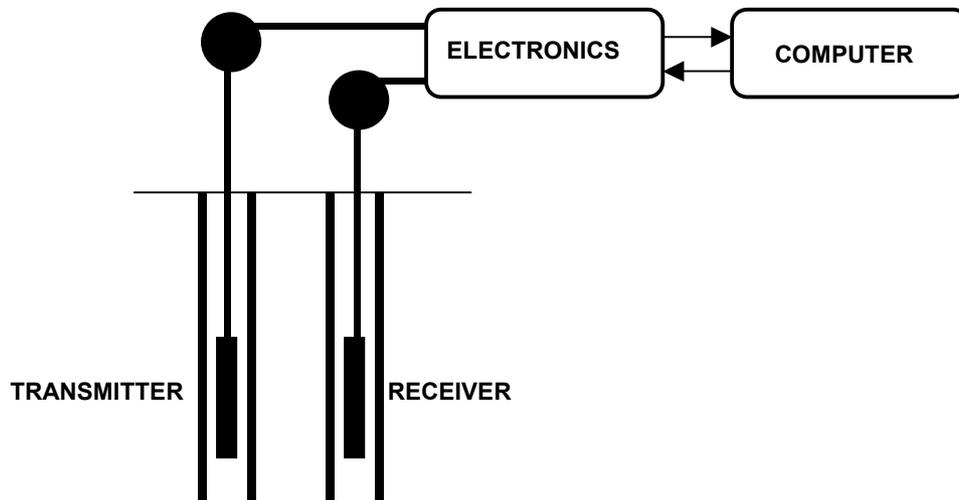


Figure 1: Cross-hole ultrasonic method

Integrity testing of piles – non-standard methods

Radioactive method

Radioactive testing (Preiss and Caiserman 1975) consists of lowering a gamma-gamma probe into an access tube. The counter connected to the probe gives a measure of the concrete density. The main advantages lie in the ability to “look around” the tube to a range not exceeding 75 mm around the tube (Davis and Hertlein 1994). Most of the probes in current use have a typical diameter of 50 mm, requiring 63 mm (2.5”) internal diameter access tubes. To avoid the influence of the surrounding soil, the tubes have to be moved away from the sidewalls by mounting them on omega-shaped spacers. These arrangements, plus the fact that the test utilizes dangerous radioactive materials (the handling of which necessitates a special license) make the test unsuitable for small diameter piles.

Single hole ultrasonic test (SHUT)

SHUT (Weltman 1977) is a derivative of cross-hole testing. It has not yet been standardized and is, therefore, an in-house method. It was originally developed for cases where the pile was checked by core drilling, in order to increase the range of the inspection. The special combined transducer produced for this purpose had a diameter of 55 mm and a length of not less than two meters. The system reportedly succeeded in discovering flaws, but because of its bulk was subsequently abandoned.

SHUT was described in more recent literature (Brettman and Frank 1996), this time with separate transducers of the type used in cross-hole testing (Figure 2). The tubes

used were either plastic or steel, and the authors reported the detection of planned defects covering between 25% and 64% of the pile's cross section. No details were given about the spacing between the transducers.

Brettman et al. (1996) used SHUT on augered cast in place piles, using both PVC and steel tubes. Some of the tests were carried out in wet grout, immediately upon completion of grouting, and the authors claimed success in locating planted defects. However, in a more recent publication, the first author (Brettman 2000) recommends that testing be done in PVC tubes, and at an optimal age of three days.

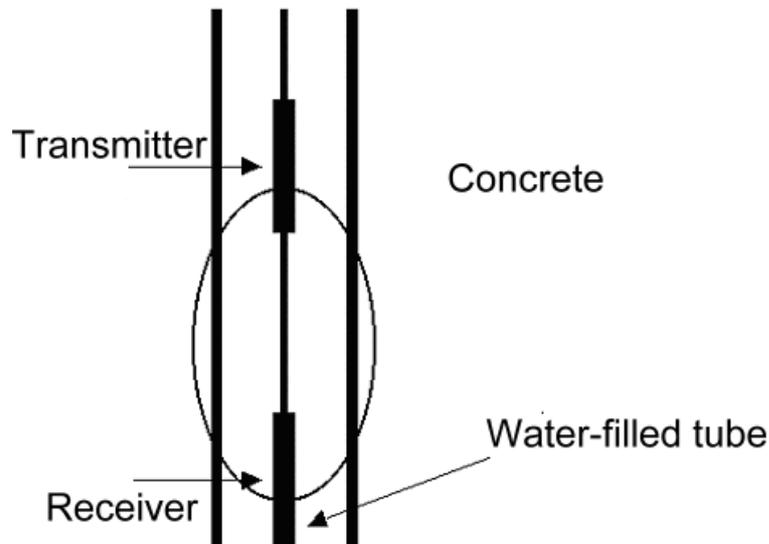


Figure 2: Single hole ultrasonic testing

Description of work

Research goals

The research work described below was intended to check the suitability of SHUT for the integrity assessment of small diameter piles. Specifically, the following points were to be investigated:

1. The suitable tube material (plastic/steel)
2. Smallest feasible tube diameter
3. Optimal tube location
4. Optimal timing of the test after concreting
5. Effective range of the test around the tube
6. Threshold size of flaws that can be identified by the method
7. Optimal spacing between transmitter and receiver.
8. Possible development of dedicated equipment for single-tube testing.

Test site

Field-testing was done on a construction site at Ma'ale Modi'in. The ground conditions of the site are typical for many sites where small diameter percussion drilled piles are

commonly specified: Very hard, jointed dolomite rock, with abundant clay pockets and penetrations. Altogether, ten piles were constructed, each with a nominal diameter of 350 mm and a typical length of 3.50 m. Eight of the piles contained known pre-fabricated voids, made out of thick plywood and sheet metal boxes (Figure 3), at a depth of between 1.50 and 2.00 from the top of the pile. A detailed list of the defects is presented in Table 1. The piles were cast under careful supervision, to ensure that they would contain no defects in addition to the planned ones.

Testing method

All ultrasonic logging was performed using the CHUM instrument manufactured by Piletest.com Ltd., equipped with 25 mm dia. probes of a 50 kHz nominal frequency. The transducers were lowered into the water-filled tube, until the lower one touched the bottom. The test was performed while pulling both transducers together upwards. Ultrasonic pulses were transmitted every 10 mm, with the instrument recording the pulse shape as intercepted by the receiver, the FAT and the relative energy, all as a function of depth. Typical pulses in good concrete and in the presence of a defect are presented in Figure 4.

The first test was attempted immediately after concreting was completed. It was discovered that the pulses recorded at this stage are extremely weak and noisy, producing no significant information. Further testing was done 24 hours, three days and after six days later, with transducer spacing varied between a minimum of 320 mm and a maximum of 900 mm.

In addition to the above, similar testing was done in PVC tubes in the open, in order to study the effect of tube diameter on wave propagation in water.

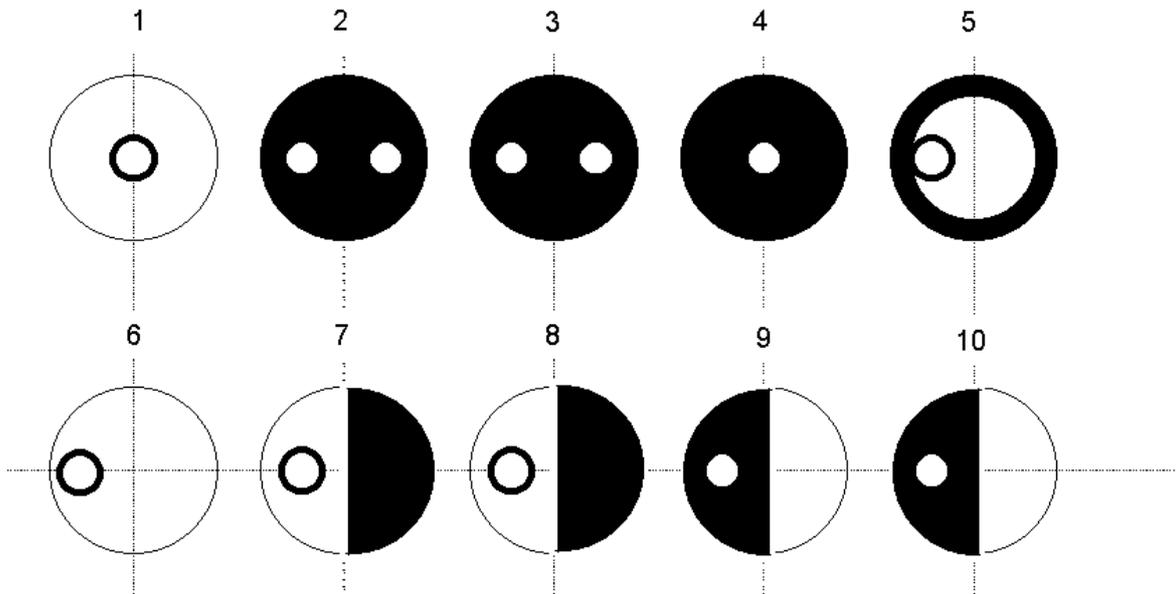


Figure 3: Scheme of defects in the test piles

Table 1: Test pile details

Pile	Description	Height	Tube	Location
1	No defect	-	PVC	Center
2	Complete discontinuity	30	PVC+steel	Side
3	Complete discontinuity	100	PVC+steel	Side
4	Complete discontinuity	100	PVC	Center
5	Ring	30	PVC	Side
6	No defect*	-	PVC	Side
7	50% reduction	30	PVC	Side, out of defect
8	50% reduction	100	PVC	Side, out of defect
9	50% reduction	30	PVC	Side, inside defect
10	50% reduction	100	PVC	Side, inside defect

* A ring-shaped defect, 100 mm high, was planned. During lowering it was found that a clay pocket squeezed in and rendered the insertion of the plywood box impossible

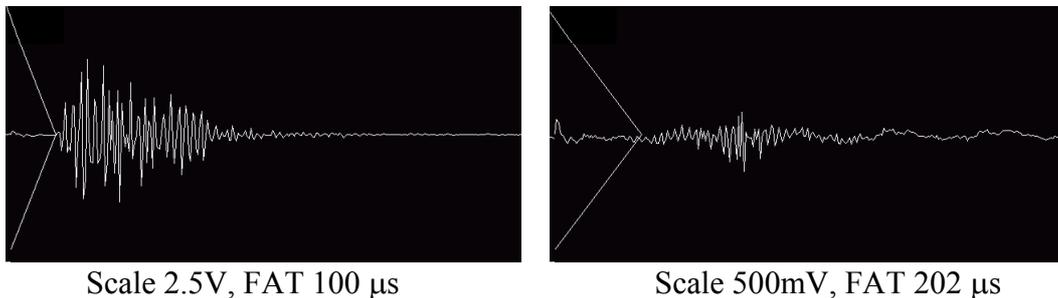


Figure 4: Typical pulse shape in good concrete (left) and with a defect present (right)

Test Results²

Tube material

To study the influence of tube material on the results, those obtained in the PVC tube of pile No. 2 were compared to those recorded in the steel tube. In each of the tubes, the test was repeated four times, at respective transducer spacings (bottom to bottom) of 320, 500, 700 and 900 mm. All these tests were carried out at the age of six days.

² All test results (raw data) may be found at <http://www.piletest.com/papers/shut>. CHUM software is available at <http://www.piletest.com/download.htm>

From the results, it is evident that the two tube materials lead to totally different results: In the PVC tube, FAT values correspond to a wave velocity of 4,100 m/s, which is typical of ultrasonic P-wave propagation in good quality concrete (Figure 5). It is evident, therefore, that in this case the waves traveled from the transmitter to the receiver through the concrete surrounding the tube. In the steel tube, on the other hand, the FAT values indicated a wave velocity of only 1,600 m/s – very close to the wave velocity in water (Figure 6). Clearly, the steel walls prevented the waves from exiting the tube.

This phenomenon can be readily explained by reverting to Snell’s law of refraction:

$$\frac{\sin(\vartheta_1)}{\sin(\vartheta_2)} = \frac{c_1}{c_2}$$

In which ϑ_1 is the angle of incidence, ϑ_2 is the angle of refraction and c_1 and c_2 , respectively, are the P-wave velocities in the two media. When P-waves travel from a medium with low velocity to one with a higher velocity they refract and move away from the normal at the point of incidence until, at a critical angle ϑ_{cr} , they move along the interface.

Typical values of P-wave velocities appropriate to this problem are presented in Table 2. When these values are substituted in Snell’s law, it is easily shown that when waves travel from water into the PVC the refraction is minimal. Then, as they exit the PVC into the concrete, they move away from the normal, and can therefore assume any angle between -90^0 and $+90^0$ to the horizontal. Some of these waves will, therefore, travel through the concrete along the outside wall of the tube and eventually reach the receiver.

On the other hand, when the waves exit a steel tube into the concrete they approach the normal, and form a bundle limited by an angle of $\pm 48^0$ with the horizon. Such a bundle cannot reach directly from the transmitter to the receiver (Figure 7).

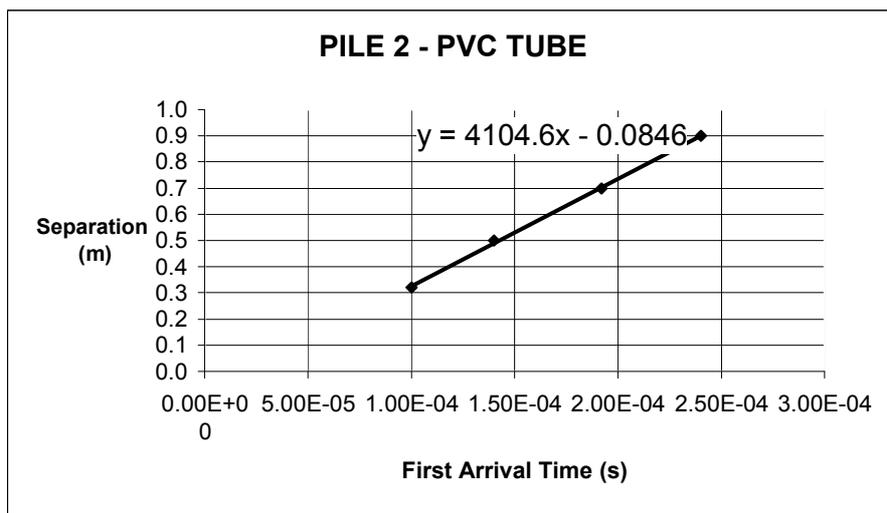


Figure 5: Probe separation vs. FAT - PVC tube

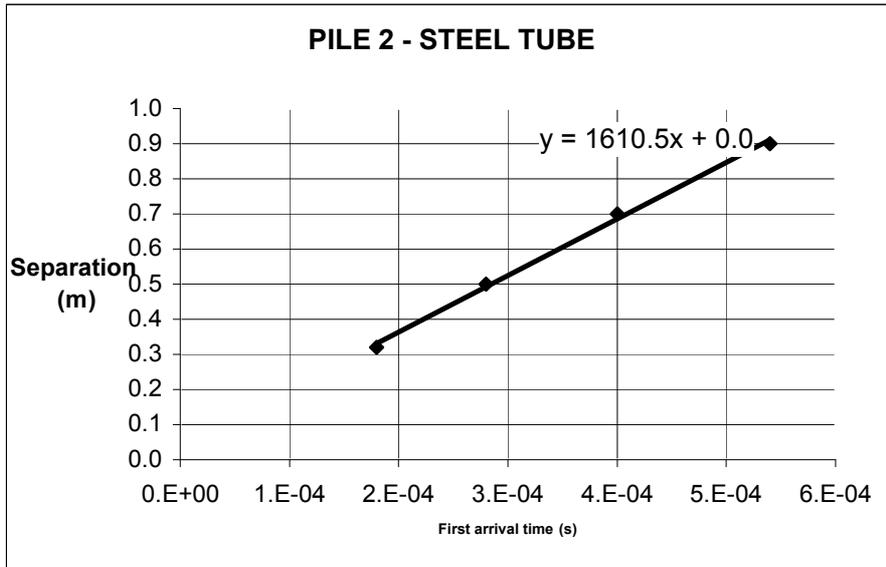


Figure 6: Probe separation vs. FAT - steel tube

Table 2: P-wave velocities in different materials

Material	P-wave velocity (m/s)
Water	1,500
Concrete	4,400
Steel	5,960
PVC	1,700

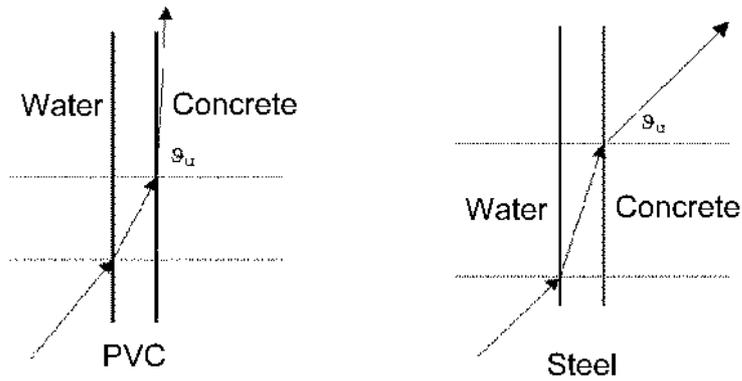


Figure 7: Wave refraction in PVC (left) and steel (right) tubes

Optimal tube size

The tube diameter has both operational and economical implications: When the tube is too narrow, there is a danger that the sensors will become jammed. A larger tube, on the other hand, is more expensive and may be difficult to fit in a small diameter pile. From initial tests done within the framework of this project, it emerged that the pile diameter has another effect:

One of the main problems that arise in SHUT is the separation between the two components of the signal: the one passing through the concrete and the one passing through the water. To investigate this effect, tests were run in water filled PVC tubes standing freely in air. Two diameters were compared: 40 mm and 50 mm, with probe separations ranging from 340 mm to 1 m.

In both tubes, the wave velocity obtained was around 1,500 m/s – a reasonable result for water. All the same, in all probe separations a marked difference between the tubes was found with regard to the energy: Typically, the 50 mm tube transmitted 4.6 times more energy than the 40 mm tube. Taking into account that the wavelength in water (33 mm) is close to the diameter of the smaller tube, one would expect small changes in diameter to have a large effect on the behavior of the wave. Clearly, the smaller tube filters the noise (water-carried energy) more effectively and facilitates processing of the actual signal.

Tube location

Locating the tube in the center of the pile minimizes the distance between it and any potential flaw. In reality, this is not easy to implement, especially when the specification call for concreting with a tremie pipe or a concrete pump with a long extension. The only practical location, therefore, is next to the spiral reinforcement, similar to the longitudinal rebars. To look into the effect of the location, a comparison was made between three pile pairs, as follows:

Full discontinuity 100 mm high – piles 3(PVC) and 4: Comparison at the age of six days (Figure 8) shows little difference between the central and the off-central positions.

50 percent reduction - 30 mm high – piles 7 and 9: In pile no. 7, where the tube is at a distance of 70 mm from the defect, no respective anomaly was observed after three and six days. A longer FAT was found after 24 hours, however, with no change in energy. This outcome seems irregular, and is probably due to concrete that had not cured sufficiently.

In pile no. 9, where the defect surrounds the tube, a high quality anomaly was obtained after 24 hours. At three days the defect became almost invisible, with a marked improvement after six days. The anomaly becomes clearer when the probe separation is increased.

50 percent reduction 100 mm high – piles 8 and 10: After 24 hours the defect produced no anomaly in the results of either pile. After three days, a decrease in energy became obvious, with no change in FAT. After six days, the defects in both piles were clearly indicated by the results (Figure 9), although in the smallest separation (320 mm) only the energy was affected.

In summary: The tube may be attached to the inside of the spiral reinforcement and still give an indication to significant defects, even when those are distant from the tube.

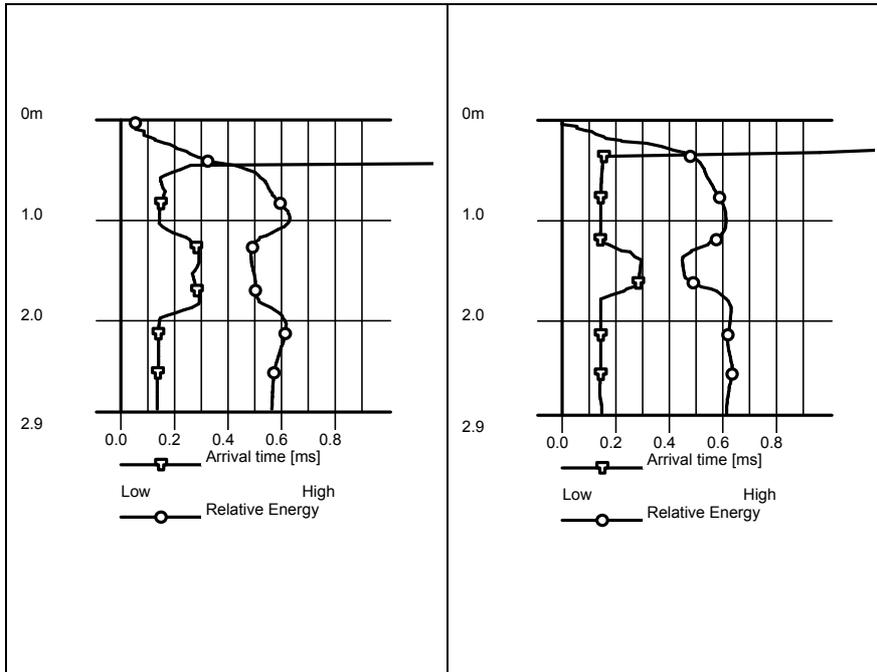


Figure 8: Full discontinuity 100 mm high - tube located off-center (left) and centrally (right)

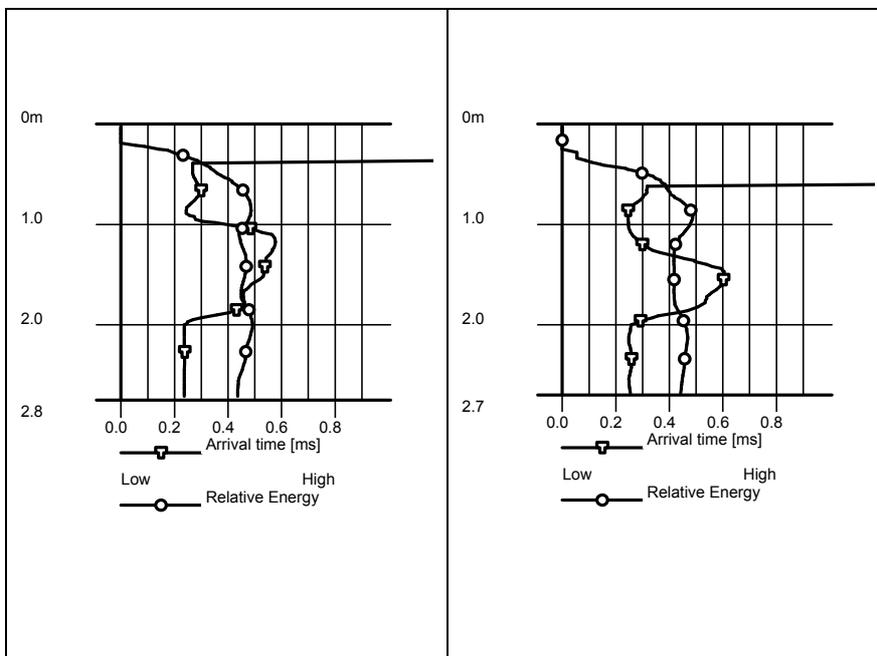


Figure 9: Fifty percent reduction, 100 mm high – tube located inside defect (left) and out of it (right)

Optimal probe separation

In all piles where the defects were discernible, it was found that increasing probe separation S enhanced the anomaly, probably due to the increased effective range (Figure 10).

Increasing the probe separation has also some drawbacks that, within a tense client-contractor environment, may create additional friction:

1. The logged pile length is shorter by S than the actual length (Figure 11).
2. The separation S serves as a convolution kernel, making the vertical dimension A of the anomaly larger by S than the vertical dimension of the defect. This relationship is valid only in the central zone of the pile, in which both probes make a full pass of every point. In this zone, the lowest point of the anomaly coincides with the lowest point of the defect.
3. In both upper and lower zones (a distance S from the head and from the toe, respectively) the vertical expansion of the anomaly diminishes linearly from S to zero at both ends. In these zones, the anomalies recorded may produce ambiguous information with regard to both size and location of the flaw. Flaws B and C, for instance, although very different in size, will produce similar anomalies.

A special double-wheel depth meter (Figure 12) was designed for SHUT testing. The wheel carrying the lower probe turns the depth encoder, while a free-turning wheel carries the upper probe. The test is performed as usual, with both probes pulled simultaneously, until the upper probe reaches the head of the pile. It is then stopped, and the lower probe only pulled until it touches the upper one. With this system the pile length obtained is almost correct, and the flaw position is indicated by the upper boundary of the anomaly.

It must be stressed, however, that the use of SHUT anomalies to locate flaws in the pile is a physical inverse problem, and as such has no unique solution.

Timing of the test

Contrary to some suggestions made in the past, it was impossible to get any significant results testing the freshly poured concrete. 24 hours later, it was difficult to obtain quality results even with the smallest probes separation.

At an age of three days, typically good results were obtained in all piles, even for a separation of 700 mm. After six days the maximum separation may be increased to 900 mm, with a corresponding improvement in the results (Figure 13).

Detection range and threshold flaw size

As expected, the detection range depends on the size of the flaw: A 50 percent reduction may readily be observed, even when it is only 30 mm in height, provided it surrounds the tube. However, a 50 percent flaw is clearly detected if its height is 100 mm, but invisible when its height is merely 30 mm.

A ring shaped flaw surrounding the reinforcement cage produced no anomaly. Considering that its dimensions are small with relation to the wavelength (80 mm) this result was expected.

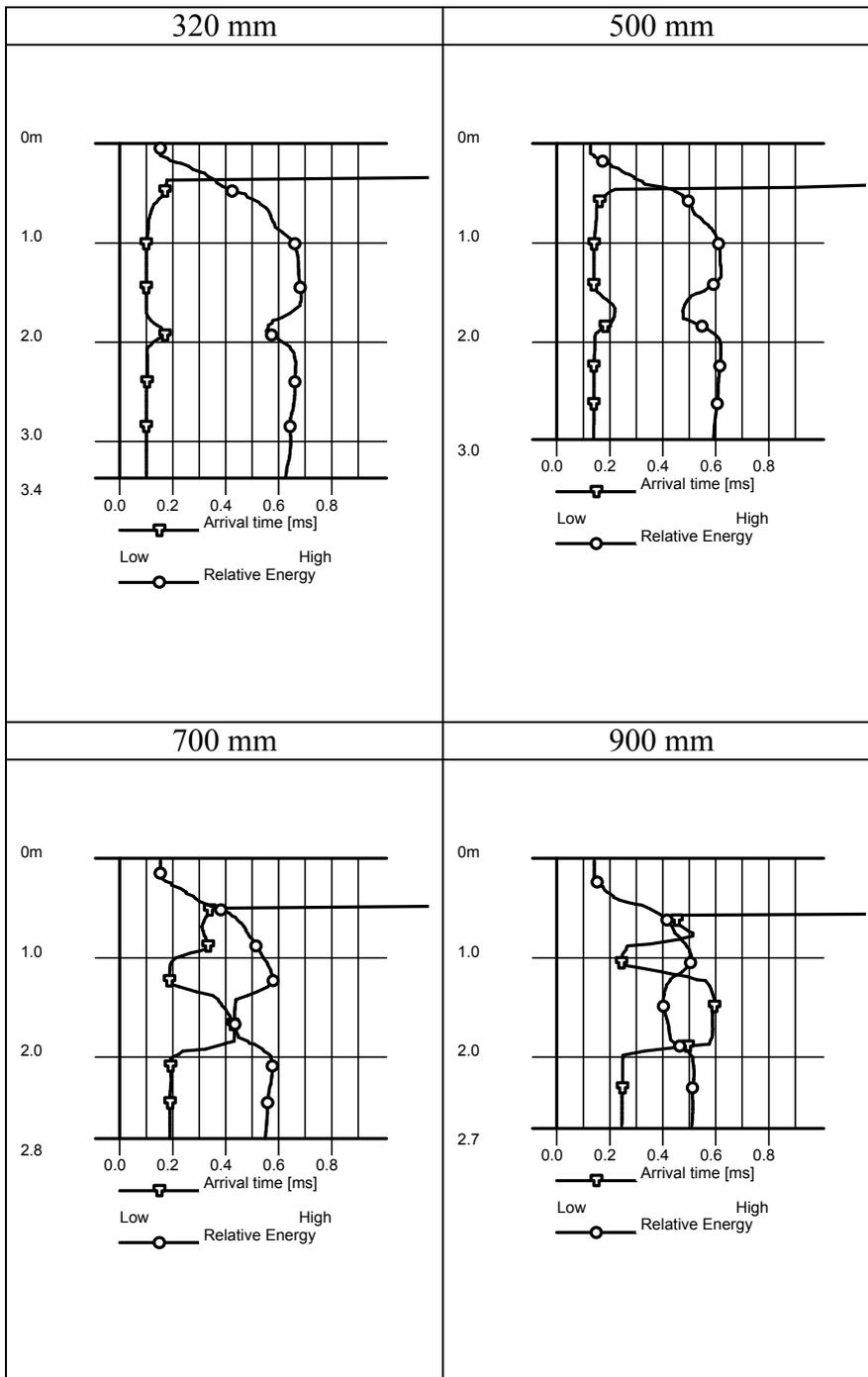


Figure 10: The effect of probe separation on the anomaly

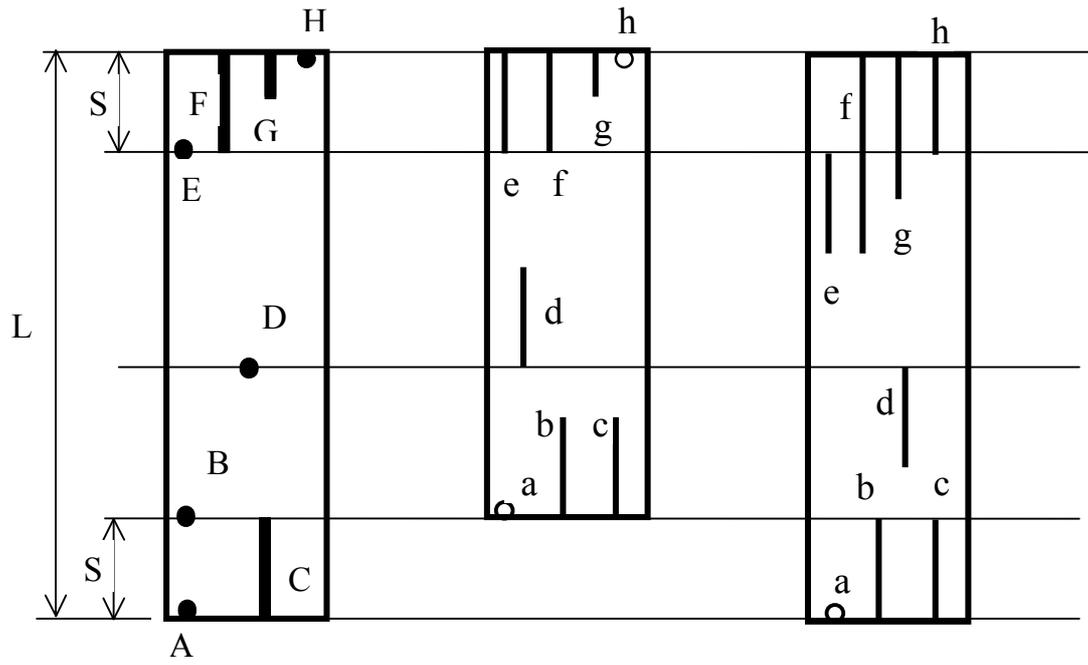


Figure 11: Actual flaws (left), logged anomalies with fixed separation (center) and with a double-wheel depth meter (right)



Figure 12: A double-wheel depth meter

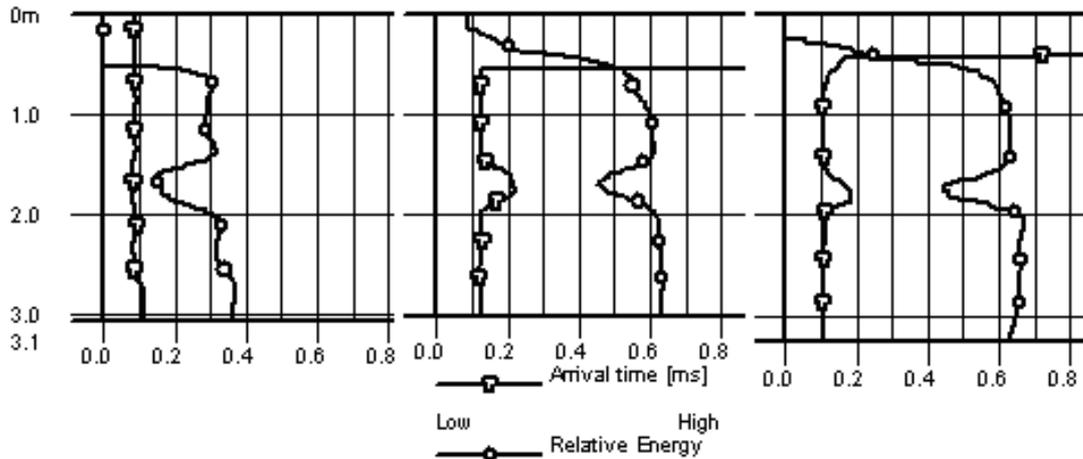


Figure 13: Tests on pile no. 4 at 24 hours (left), 3 days (center) and 6 days (right)

Conclusions

1. Single-hole ultrasonic testing (SHUT) has proved to be a viable approach to assess the integrity of small diameter piles.
2. For SHUT, the use of plastic access tubes is mandatory. Steel tubes concentrate the waves in a relatively narrow horizontal bundle, thus preventing the propagation of waves from the transmitter to the receiver.
3. For the tubes, the smallest practical diameter should be specified. A PVC tube with an internal diameter of 40 mm is a satisfactory solution for 25 mm diameter probes.
4. The tube may be tied to the inside of the reinforcement cage, the same way as the longitudinal rebars.
5. The piles should be tested no sooner than three days after casting, and a five to six day waiting period is preferred.
6. Flaws are usually shown as anomalies, consisting of delayed first-arrival times (FAT) and decreased energies.
7. Because of convolution by the probe separation, the vertical size of the flaw is generally increased upwards. Both size and location of flaws close to the head and to the toe tend to be distorted.
8. SHUT can discover rather thin flaws, provided they surround the tube. Thicker flaws may be found at ranges exceeding 70 mm from the tube.
9. Since it combines superior performance with zero radiation risk, SHUT may supersede radioactive testing of large diameter piles.
10. Increasing the separation between the probes leads to an enhanced anomaly resolution. On the other hand, it reduces the reported pile length, displaces the anomaly and increases its vertical dimension. The use of a double-wheel depth meter may help to overcome some of these drawbacks.

Appendix I. References

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