Sonic echo pile integrity testing and quality control

by OSWALD KLINGMÜLLER, GSP, Mannheim, Germany.

Abstract

When low strain integrity testing is carried out on cast in situ piles, there is a remarkable danger that a certain percentage of piles will be rejected. This might easily lead to very awkward situations for site management, especially as there is usually little time on a building site between installation of the piles and agreement upon the results of the integrity tests. The necessary actions in case of a rejected pile have to be considered when the piling equipment has probably passed to another site and the site may even not be accessible for any kind of heavy equipment. The optimum benefit from pile integrity testing can be best gained, if the method is used as a tool of quality assessment. But that means that the method has to be carefully embedded into the construction schedule and work programme of a building site in co-operation of client, consultant and contractor. The problem is discussed and the proposal for application demonstrated with respect to different site experiences.

Introduction to the method and quality indicators

Low strain integrity testing is a tool of quality control of cast in situ concrete piles. Based on the phenomena of wave propagation in solids (see **Figure 1**) information on shape and length of a pile can be gained by a simple blow with an ordinary hammer.

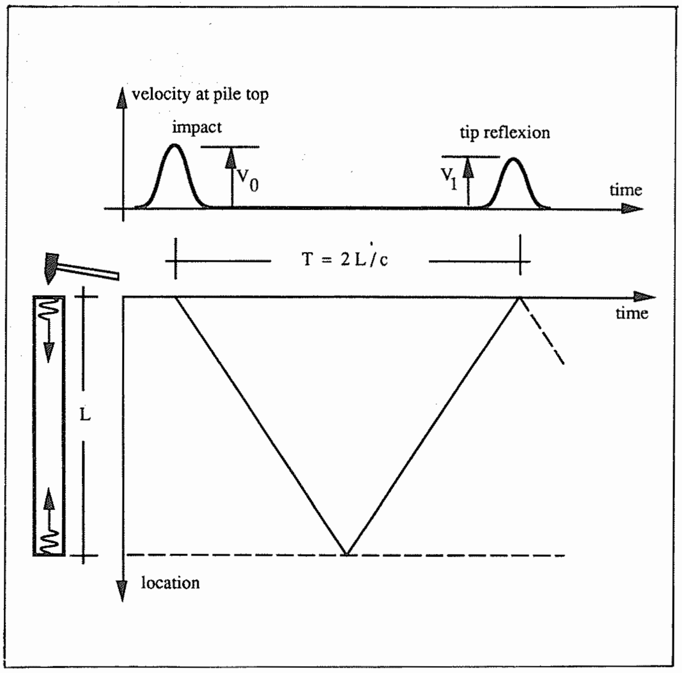

Figure 1: Basic principle of low strain integrity testing.

Dr Oswald Klingmüller is managing director of Gesellschaft für Schwingungsuntersuchungen und dynamische Prüfmethoden (GSP).

The time history at pile top can show the features of the pile hidden in the ground. If the velocity between impact and reflection stays at zero, the pile can be assumed to be of constant cross section with no changes in the soil conditions. The velocity time history graph in Figure 1 indicates a prismatic bar of constant cross section, that is free from contact to any environment. Deviations therefore reveal either a variation of pile cross section (or a variation of internal material characteristics) or soil influence.

In simple cases the interpretation of the signals will be successful because of the experience of the tester under assumptions of one dimensional wave propagation. For general cases however, with interaction of cross sectional shape deviations, degradation of concrete quality and special soil conditions, theoretical solutions and computer simulations can be applied. These advanced tools are nowadays available under several names (PITWap, TNOWave, etc).

Independent of the interpretation of the individual features of the signal, the relationship of pile length and wave velocity should be evaluated carefully. The travel time of the impactive wave from top to bottom and back to the top is related to the pile length and the velocity of wave propagation of the pile material by

$$T = \frac{2L}{c}$$

where T: travel time of the impactive wave from top to tip and back,
L: pile length from transducer to pile tip,
c: velocity of wave propagation (material constant: $c_{concrete} = 3.5 - 4.0$ m/ms, $c_{steel} = 5.7$ m/ms).

The velocity of wave propagation as a material constant incorporates the piles density and elasticity

$$c = \sqrt{\frac{E}{\varrho}} ,$$

where E: elastic modulus of pile material (Young's modulus),
ϱ: density of pile material.

As the density is quite stable, even if the concrete mixture might not be correct, the velocity of wave propagation is closely correlated to the elastic modulus, and therefore the velocity of wave propagation is a clear indicator of the quality of the pile material.

Assuming that the length of the installed pile equals the length prescribed by the design, the velocity of wave propagation is calculated by

$$c = \frac{2\,L_{plan}}{T_{measured}}$$

As long as the value of c lies between the boundaries known for concrete, the pile can be assumed to be of correct length and correct material. If c is less than the lower boundary, either the pile will be too long (which is unlikely but not impossible) or the concrete lacks strength. If c is larger than the upper boundary, the pile will be too short or the strength of the concrete exceeds reasonable values (which again is unlikely but not impossible).

If the velocity of wave propagation can be determined exactly by material testing or by means of a test length at a partly excavated pile, the actual length of the pile is given by the inversion of the above formula

$$L_{pile} = \frac{c_{exact} \cdot T_{measured}}{2}$$

The evaluation of actual pile length or velocity of wave propagation has carefully to take into account the scatter of the values and the age of the pile.

Another indicator for pile quality can be the relationship of the induced impact velocity v_0 to the reflected velocity v_1. By the theory of one dimensional wave propagation, it is known that the reflected velocity must be twice the impactive velocity for an ideal prismatic bar without any damping and without contact to the environment at the boundaries.

In structural dynamics damping is measured as percentage of critical damping. The logarithmic decrement δ defines the relationship of neighbouring peaks in the time history of a damped oscillation and is related to the structural damping by

$$\delta = 2\pi D$$

In wave propagation phenomena, the time domain is related to the space domain by the velocity of wave propagation as a material constant. For T_0, being the period of the oscillation and therefore the time between neighbouring peaks, the length between neighbouring peaks for a travelling wave becomes

$$\lambda = c\,T_0$$

By this relationship the attenuation of the impact wave with respect to the length of the pile can be calculated.

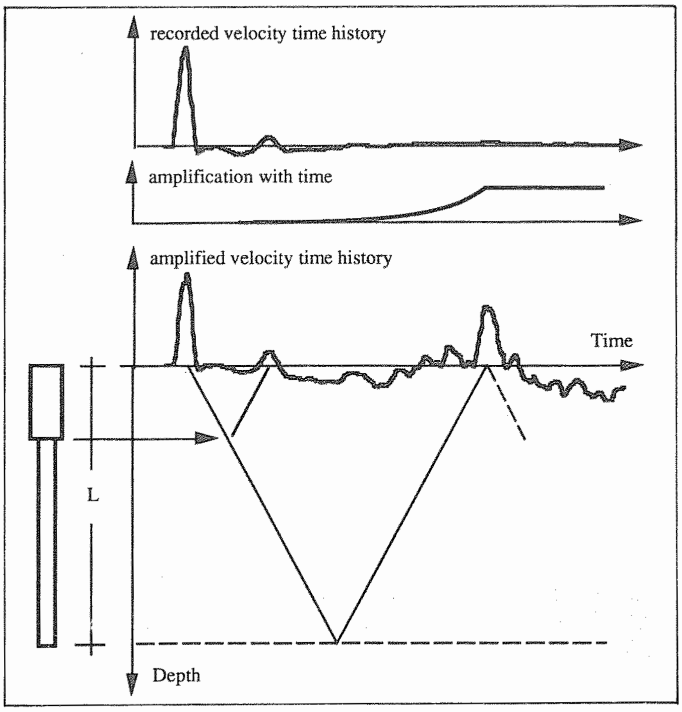

Figure 2: Amplification of velocity time history for damping compensation.

If for pile concrete a value of D = 5% is assumed, the governing period of the impact is taken as 10^{-3} seconds (1 ms) and the velocity of wave propagation of 3.5m/ms is assumed, the attenuation of the impactive wave will be 0.9/m. For a pile length of 12 m the reflection should have an amplitude of

$$v_1 = 2 \cdot 0.9^{24} \cdot v_0 = 0.16 \cdot v_0$$

(The number 2 corresponds with the theoretical solution, the power of 24 corresponds with the total travel path of the wave).

In general the reflected velocity will be very much less than this value, because the irregularity of the pile cross section and the soil friction have a great influence by differential refraction of the impactive wave.

To compensate the loss in the reflected signal due to damping or any refraction of internal material variations or external effects of the surrounding soil signals, an amplification with time is useful. In **Figure 2,** for a 23m long flight auger pile a maximum magnification of 30 provided a clearly distinguishable tip reflex. It has to be taken in mind that together with the amplification of the tip reflex, all other signal features, especially baseline offsets, are also amplified (Figure 2). These effects have to be taken account of in the interpretation of the signals.

Experience shows a clear dependency of the relationship of v_1 to v_0, but an understanding of how to use the value as an indicator of the pile quality, needs a large sample of systematically collected data that have to be evaluated statistically.

Problems with current practice

In some countries (eg Austria[1]), the usefulness of the method has been acknowledged and testing has been codified accordingly. With such a codification a certain benefit can be given with respect to safety factors.

Other countries (eg Germany[2], Eurocode 7[3], cf.[4]) have not introduced low strain integrity testing as a means of quality control. Only recommendations exist with respect to the execution of the tests. Therefore, when the tests are carried out, this happens mostly in a hostile environment, where consultant, contractors and authorities argue about the real quality of the pile.

Consultants and authorities might have their reasons to mistrust the work of the contractor, because, for example, of concrete quality in pile tops that have been excavated, or because the concrete consumption deviates from the planned volume of the pile. In these cases an independent statement on the true quality of the pile is demanded, and a low strain integrity test is specified.

But the tests have to be carried out under quite adverse circumstances. Often because of the number of meetings that have taken place, the construction works on site have reached a state where most of the good piles have already been incorporated into the structure, ie base slabs, foundation grid works and such. The piling contractor finally gives in and orders a test of the questionable piles, insisting that the tests are carried out in the instance after the telephone call, and the results are presented immediately afterwards.

The tester who is employed for the job faces a very awkward situation:

1. The tests have to be carried out under the sceptical surveillance of the consultant and authority engineers as well as under the eyes of the piling contractor, which might not be too sure about the quality of the piles. Curious and interested colleagues of either side will also be present.

2. Often, there has not been much time to prepare the surface of the pile and to bend away the reinforcement, so that the application of the acceleration pickup and the hammer blow becomes sweat driving tasks.
3. The most questionable pile is almost always the one to be tested first, and after the first hammer blow bystanders around want to know all about it.
4. When the pile shows severe defects and must be rejected the possible actions are:
   a) excavating and installing a new pile
   b) installing a new pile next to the other.

In the second solution, a recalculation of the foundation construction is needed for the load transfer to the new pile position.

Usually, at the time of the integrity testing, the piling equipment has been moved to another site or at least to a remote part of the site, where piling is still going on. Pile concrete should be at least seven days old for the execution of low strain integrity tests, so it can be assumed that, at the area of the tested piles, construction works have been going on and reached another state. With the installation of an additional pile, there will be another interruption of the construction work, and the site has to be prepared to put the heavy piling machinery in place. All this at the cost of the piling contractor or his insurance and all this because of the result of low strain integrity testing.

In most cases, the total cost of the piling will be less than the cost of an additional pile.

As low strain integrity testing is comparably cheap, it is ordered without a thought towards the consequences.

For the tester this means that the negotiations have to be conducted carefully and the following should be observed:
1. Not to be forced to render statements by the test of a single pile, but always try to have a number of piles for comparison, so that an average good pile for a site can be defined.
2. Not to promise results that cannot be supported by the testing method (ie deviations within the range of 10% or less).
3. Not to promise results that cannot be supported by the one dimensional wave theory (eg one sided bulges or neckings).
4. To definitely state that the application of the method is confined to concrete piles of constant cross section with pile depths of up to 15m.

If, by experience or the specific properties of the piles at the site, the tester can give one sided or less than 10% deviations or results for longer piles or for piles inserted in construction, these can be produced as additional results. If the situation is not presented like this, the tester may face severe difficulties, when explaining the reasons for not being able to produce these results.

Example for testing of questionable piles

The following is an example of testing a pile used in the remedial strengthening of an old industrial bridge support. Pile integrity testing was asked for because during construction an unplanned prerigidification was indicated as the casing of a cast in situ pile was pulled. The pile on the other side of the old foundation did not show any deviation during construction. By the time the integrity testing was carried out, the piles had already been connected to the final superstructure (see **Figure 3**), so it was only possible to test the piles by indirect blow on top of the attached foundation blocks.

The client could be convinced that the result of the test would be much more reliable if both the pile in question (left side) and the pile that did not show any deviation during construction were tested.

With only the results of the tests of the left pile, it would be

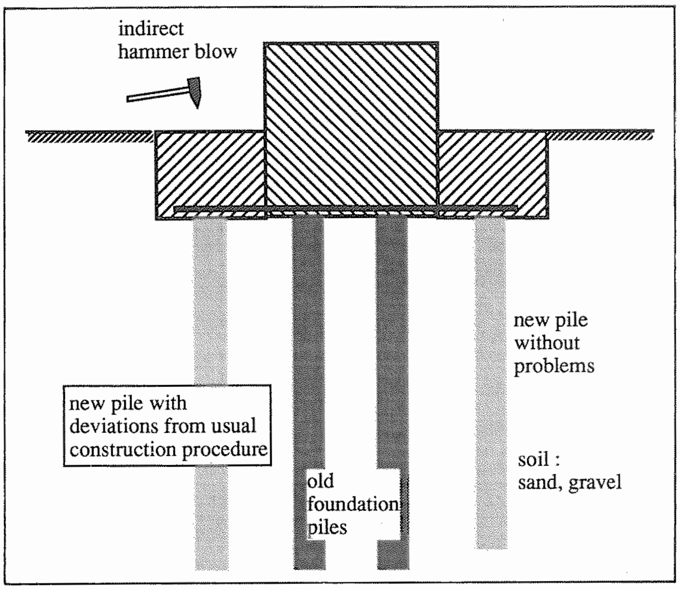

Figure 3: Foundation strengthening with attached blocks and piles.

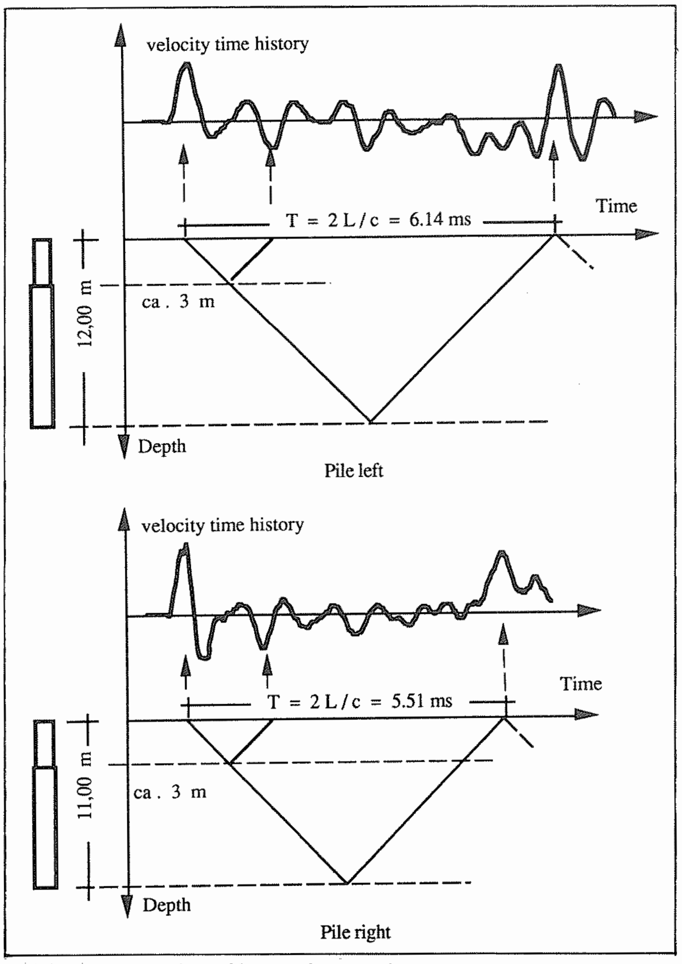

Figure 4: Results of integrity testing.

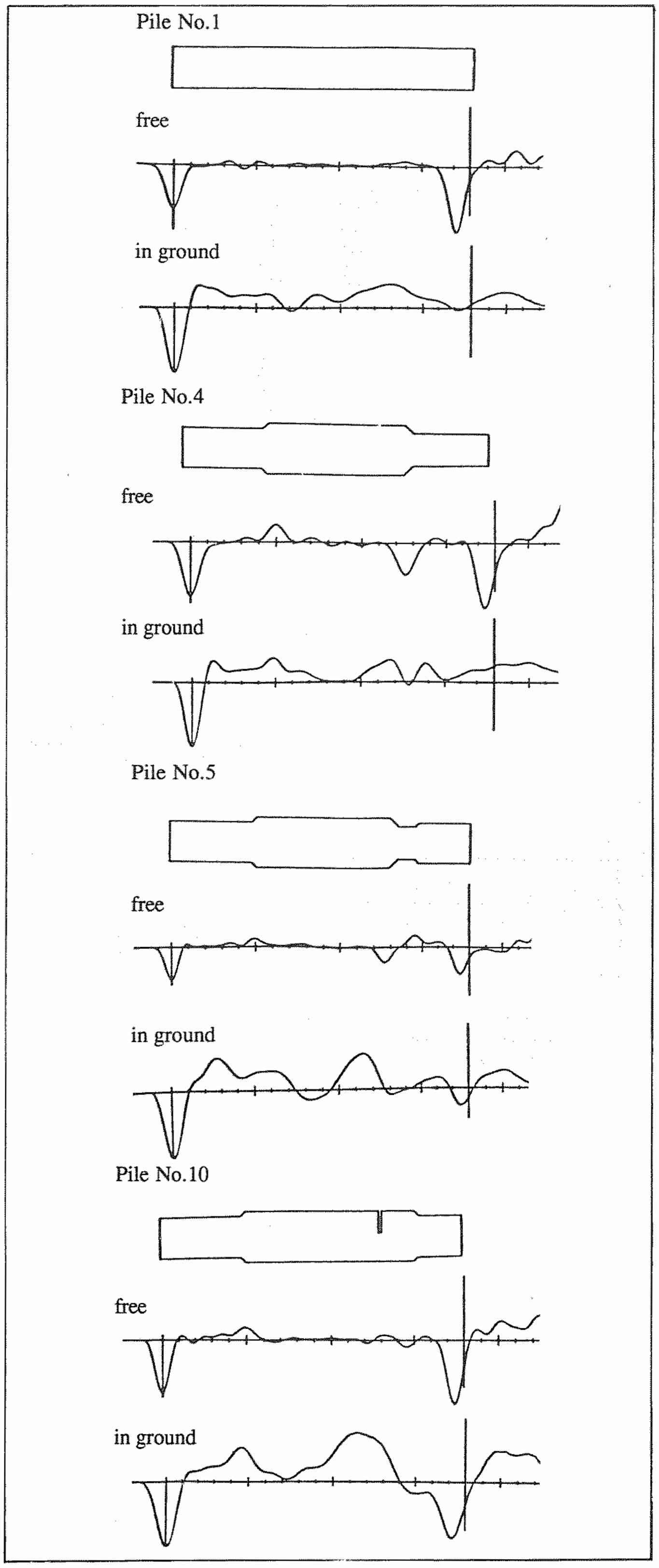

Figure 5: Integrity tests of prepared piles.

difficult to give a reliable interpretation. When the two piles are compared to each other, it could be recognised (**Figure 4**), that they are showing the same features and thus it could be concluded that, if the right pile is accepted, the left pile can also be accepted. The deviations of the time history graphs from a straight horizontal line can be associated with reflections from the several discontinuities of the attached foundation. As the signal does not show any reflection with velocity increase (similar to the impact) before the reflection of the pile bottom, a reduction in cross section can be excluded.

From the interpretation of the two tests it can be concluded, that the travel time is the main reliable quality indicator, as both piles have equal wave propagation velocities.

Application window of integrity testing as defined by demonstration piles

In last year's fourth conference on the application of stress wave theory to piles, a number of ten test piles were prepared in order to have a competition of integrity testers[7]. As many foundation engineers are sceptical about the reliability of the testing methods, these testing competitions are quite attractive. In 1983, three prepared piles for integrity testing were installed in a site in Germany (results have been reported[6,8], and in 1987 the Belgian Group of the International Society for Soil & Foundation Engineers had organised a pile test competition with 24 piles, ten of them specially prepared for integrity testing[5]).

The ten piles of the Stress Wave Conference 1992 were precast concrete piles with a square cross section of 250×250mm. The defects were increases in cross section to 300×300mm and decreases respectively, and some piles had horizontal slots cut into them. Two identical piles of each type were prepared. One of each could be tested lying on a raft in the open, the other one had been installed in an 1m diameter casing filled with different soils under different compaction conditions. As complete test results are published elsewhere[7], only four measurements are presented here (**Figure 5**).

As can be learned by the graphs in Figure 5, the steps in the cross section are clearly indicated by the signal for the free pile. The cuts, however, do not show. This is of course due to the relationship of the length of the impactive wave, app 0.5ms, which equals a portion of 2m length of the pile being under compression compared to the distance between decrease and increase of the cuts, 100mm (app 0.04ms). Thus the refraction of the signals for a decrease is overlapping the refraction for the increase, and nothing can be seen in the velocity time history on top. The only indicator for the cuts could be a reduction in the intensity of the reflected signal. To reveal the cutting by this reduction, extensive computer simulation must be executed.

Other important knowledge can be gained by the inspection of the buried piles. Whereas pile 4 and pile 10 show the increase of the cross section clearly, in pile 5 the increase is in this recording hidden by the soil influence. Also the decrease in the cross section, that is clearly shown for the free piles, is producing very different shapes in the signals of the bured piles. Even pile 1, which has no specialities whatsoever, shows, when installed into the ground, several ups and downs in the velocity time history that may give rise to doubts regarding the quality of the pile.

The situation in this competition is therefore different from a real testing situation, because all installed piles have their individual soil conditions.

For all piles, except pile 4 after installation into the ground, the

Tables 1 to 3: Evaluation of integrity test results.

pile	depth	travel time	c = 2 L/T
72	10.50	5.61	3.74
73	10.50	5.60	3.75
75	10.50	5.53	3.80
85	6.00	3.31	3.63
86	6.00	3.10	3.87
96	10.00	6.00	3.33
97	10.00	5.64	3.55
99	10.00	5.70	3.51
100	10.00	5.50	3.64

pile	depth	travel time	c = 2 L/T
96	10.00	6.00	3.33
99	10.00	5.70	3.51
97	10.00	5.64	3.55
85	6.00	3.31	3.63
100	10.00	5.50	3.64
72	10.50	5.61	3.74
73	10.50	5.60	3.75
75	10.50	5.53	3.80
86	6.00	3.10	3.87

maximum	3.87
minimum	3.33
mean value	3.65
standard deviation	0.17
coefficient of variation	4.56%

pile end is clearly recognised, and the intensity of the reflection can be used for calibration of the other features. For pile 4 the record indicates that during the burying procedure the pile has been damaged.

Thus it can be concluded that in general the method can indicate

- the length/wave propagation velocity of the pile; and
- major cross sectional deviations, if soil influence can be distracted by comparison of different piles in the same soil.

Integrity testing as quality assurance

On a site a number of 200 flight auger piles have been installed. As a means of internal quality assurance/quality control a sample of nine piles has been integrity tested. Summarising all results, the good performance at this site is visible (**Tables 1** to **3**).

In Table 1 times from impact (T1) to reflection (T2) are enlisted and the travel time is computed. By using the relationship

$$c = \frac{2\,L_{plan}}{T_{measured}}$$

wave propagation velocities are computed.

The evaluation starts with picking maximum and minimum, and, additionally, by calculating statistical parameters such as mean and standard deviation. It can be seen, that the coefficient of variation for the wave propagation velocities at this site is in the range found for materials of structural engineering (steel or concrete).

When piles are assorted according to increasing wave propagation velocities, it can be seen, that piles 96 to 100 are grouping together with the smaller values, as well as piles 72 to 75 with the larger values. This corresponds to the difference in the time between installation and testing of the piles. For piles 96 to 100 time after installation has only been five days, whereas for the other axis a longer time has elapsed between installation and testing. With respect to concrete strength, the short time after installation, ie only few days, is responsible for the low values of wave propagation velocities.

By inspection of the time histories, only minor deviations from the ideal line can be recognised. Piles 75, 96 and 100 give an indication of a little decrease in cross section at approximately 2m. With respect to the capabilities of the method as explained in the previous paragraph, the deviations can be regarded arising mostly from the soil and as not being critical for the capacity of the pile.

Thus it can be assumed, that for this site the performance of pile installation has been excellent.

In **Figure 6** the amplification that has to be applied to equalise the reflexion to the impact is also given. For the shorter piles the amplification factors are considerably lower than for all the other piles. For a general quality statement, however, the scatter is too large. The usefulness of the amplification factors in connection with material and soil damping has to be investigated further.

In cases where all piles of a site are tested , it may be meaningful to summarise the results in a graph of relative frequencies (**Figure 7**).

The upper graph in Figure 7 has been drawn from the results of a site where 1000 piles have been tested in a quality assurance procedure, and all engaged parties have been well aware of the importance of the matter. The result is that the wave propagation velocities of the piles are grouped very closely around the mean value, and it can be said, that piles are of sound concrete and reaching to the depth planned for load transfer.

The lower graph gives an inside view into the situation, where piles are tested after the job has been finished. The wave propagation velocities are within a range from 2.5m/ms up to 6m/ms and it can be suspected that in all piles with low values (<3.0m/ms) concrete quality is poor, whereas all piles with high values (>4.5m/ms) are too short. It has been very difficult for this site to find an acceptable solution for the foundation system after the results have been presented.

Integrity testing as a tool of quality assurance

As explained by the examples in the previous paragraphs, an adequate use of the method can be made, when low strain integrity testing is fully acknowledged and incorporated into the quality control of a pile foundation.

In that case, first, a benefit can be gained with respect to piling foundation safety, and second, the execution of the method can be considered within the time schedule of the total construction. In this environment, all involved parties have first to agree to an acceptance procedure, that guarantees a joint understanding of the test results and binds them to a final decision within the reasonable time window for consequences as eg installation of additional piles. Such an acceptance procedure can read as follows:

- rules for the execution of tests
- classification of test results
  - description of signal
  - description of pile
- assessment
  - accepted = 1
  - rejected = 0

Rules for the execution are to be established in order to gain uniform test signals:

- pile top must be accessible for the application of a hammer blow, pile top must be clean, and the surface for hammer blows must be smooth sound pile concrete.
- hammer blows must be reproducible, a number of comparable blows are to be recorded.
- for the evaluation, appropriate signals have to be chosen for an averaging procedure.
- magnification and smoothing have to be the same for all evaluated signals.

Such an agreement on the execution of the tests will be the basis of a joint acceptance of the correctness of the gained signals and thus of the evaluation of the time histories. With respect to the interpretation of the signals, it must be clearly distinguished between features of the signal at a specific site and the conclusions, that can be drawn with respect to the shape of the pile.

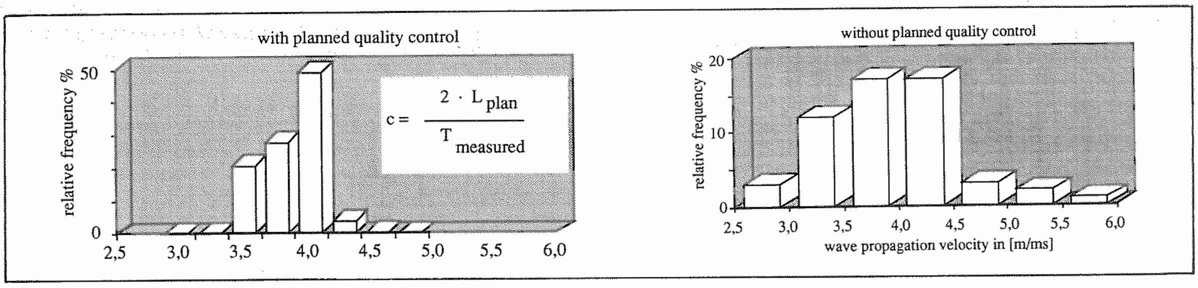

Figure 7: Relative frequencies of wave propagation velocities.

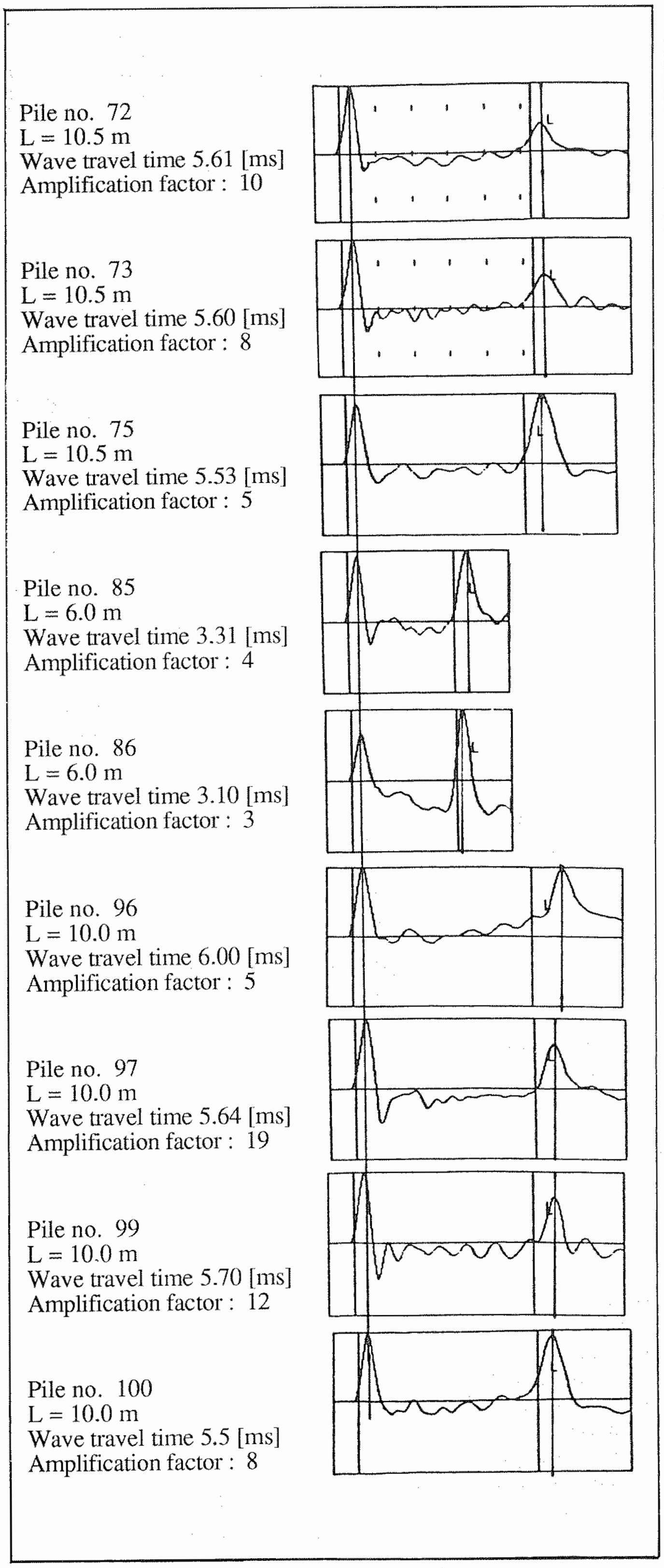

Figure 6: Pile integrity testing as quality assurance.

In the classification of test results, it can be distinguished between the features of the signal (velocity time history) or the conclusions drawn with respect to the pile:

- description of signal
  - normal time history
  - good tip reflex
  - weak tip reflex
  - no tip reflex
  - positive deviation from base line
  - negative deviation from base line
- description of pile
  - as planned cross-section
  - decrease in cross-section
  - step to smaller diameter
  - step to larger diameter
  - increase in cross-section
  - longer than according to plan
    low wave velocity (<3.5m/ms)
    poor concrete quality
  - shorter than according to plan
    high wave velocity (>4.5m/ms)
    good concrete quality (aged concrete)

Additionally it can be agreed upon to evaluate the frequency transforms as well as computer simulations such as PITWap or TNOWave.

Conclusions

Pile integrity testing is in many cases applied as a tool in the negotiations of client and contractor about the quality of the work. Answers are demanded that can be only classified within a context of belief or disbelief.

On the other hand, there are definite chances of integrity testing as a tool of quality assurance management, that can be utilised when all partners engaged in a foundation job are willing to use this tool. In that case, pile integrity testing will be very helpful to assure that all piles are of sound concrete and reaching to the depth planned for load transfer.

This capability of the method can be fully mobilised, when codification boards accept the method as incorporatible to other prescriptions for quality control (such as site reports on concrete mixture, and concrete consumption, boring depth etc) and by this give benefit to client and contractor.

References

1 Önorm B 4440 Pfähle, zitiert nach [4].
2 E Franke & JM Seitz. Empfehlungen des Arbeitskreises 5 der Deutschen Gesellschaft für Erd- und Grundbau e. V., Heft 3/1991, Geotechnik Essen.
3 Eurocode 7, Part 1, Geotechnical design, General rules, Chapter 7, Pile Foundations, Revised Draft, CEN, December 1991.
4 Jörn M Seitz. 'Low-Strain Integritätsprüfungen bei Bohrpfählen'. Bautechnik 69 (1992), Heft 10, Ernst & Sohn.
5 Groupement belge de la société internationale de mécanique des sols et des travaux de fondation, Essais dynamiques de pieux intégrité et capacité portante, Journées d'études Nov '87 Bruxelles 1987.
6 HG Balthaus & H Meseck. 'Integritätsprüfungen an Ortbetonpfählen'. TIS Tiefbau Ingenieurbau Straßenbau 9/84, Bertelsmann Fachzeitschriften, S. 470-479.
7 P Wheeler. 'Stresswave competition'. *Ground Engineering,* Nov 1992.
8 G Ulrich & M Stocker. Integritätsuntersuchung an präparierten Betonpfählen, Integrity investigation of prepared concrete piles, Meßtechnik im Erd-und Grundbau, Symposium München 1983, Deutsche Gesellschaft für Erd- und Grundbau e. V.