Critical Comparison of Ultrasonic Pile Testing Standards

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ABSTRACT: Over the last three decades, cross hole ultrasonic testing of pile integrity has advanced to maturity, and is presently considered as the most potent and sophisticated tool for the quality control of deep foundations. In parallel with the development of the method, different Standards and Codes of Practice codifying its application have been developed in three continents. These documents dwell to some degree or other on the following points: test setup and preparation, instrumentation, testing method, definition of test parameters, real time analysis, reporting format, anomaly definition and acceptance criteria.
This paper compares all available documents item by item, illuminating their strong and weak points. Since all Standards and Codes of Practice are updated from time to time, the comparison presented may serve as a convenient starting point in improving the next version. In the global village, piling contractors and testing laboratories move freely from one country to another. Since piling methods know no borders, there is no reason why their quality control should not be based on universally acceptable Standards.

1 INTRODUCTION

Producing competent bored piles is one of the most difficult tasks facing a civil engineer. Since their production process is carried out in a hostile underground environment and is largely invisible, bored piles unavoidably contain flaws. On the other hand, replacement of faulty foundation piles is at best impractical. This is the reason why quality control of finished foundation piles grew to rely on indirect imaging methods. Among these methods, an intensive research and development effort has been devoted to stress wave methods and in particular to the ultrasonic testing of pile integrity. As a result, this technique has emerged as the most potent and sophisticated tool for the quality control of deep foundations (Amir & Amir 1998). In actual field tests, ultrasonic tests managed to detect flaws occupying 10% to 15% of the cross section of the element (Sarhan et al. 2002, Iskander et al. 2003). In parallel with the development of ultrasonic integrity testing, different Standards and Codes of Practice codifying its application have been prepared in three continents. To keep abreast of technical development, all these Standards have been regularly updated with new editions published.
Globalization has brought with it free international traffic of both contractors and testing laboratories, who can perform optimally only under universally accepted codes. In this paper we present a critical comparison of the three current Standards for ultrasonic integrity testing of piles we managed to find: ASTM (2008), Chinese (Chen Fang et al. 2003) and French (AFNOR 2000). By this means we intend to pave the way for merging all these documents into an international Standard.
The comparison addresses the following items: preparation for testing, instrument specification, test procedure, FAT and energy calculation, presentation method and anomaly definition. The main requirements of the above documents are summarized in Appendix A.

2 PREPARATIONS FOR TESTING

2.1 *Number and spacing of access tubes*

The ultrasonic integrity test is of the intrusive type, which means it is usually performed in pre-installed access tubes. In rare cases the test may also be carried out in drilled holes. Access tubes are usually made of steel, although plastic tubes are quite common in the US. Whatever the material, tubes are expensive, and the engineer is expected to specify the minimum number of tubes that will give him an adequate chance to discover all important flaws. Li et al. (2005) made an attempt to correlate the number of tubes installed in a pile with detection probability of flaws. Modern ultrasonic equipment can without difficulty cover a distance of at least four meters between emitter and receiver, but the usefulness of such a large spacing is doubtful. We have shown (Amir, 2007) that detectability of a given flaw decreases with its distance from an access tube. The rule provided by ASTM limits the maximum tube spacing along the perimeter to less than 1 m. A finite element analysis we carried out (Figure 1) shows that a flaw halfway between two tubes is detectable (increase of 20% in FAT, 12 dB in attenuation) only if its size is at least 40% of the tube spacing. Thus the ASTM rule ensures detection of flaws in the order of 400 mm. Moreover, for tube spacings below 1m, oblique readings for tomography (which involve longer range) can be taken without difficulty.

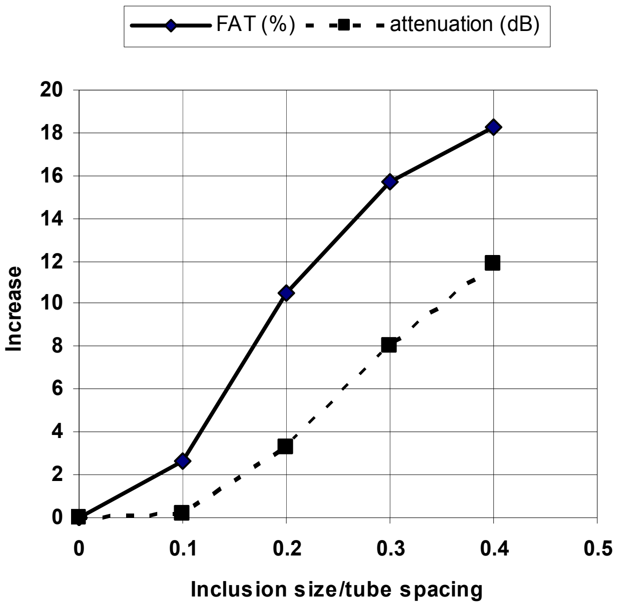

Figure 1 - Detectability of an inclusion halfway between tubes

By this reasoning, the use of only four tubes for very large diameter (3-4 m) piles, as allowed by the Chinese Standard, is far from providing sufficient covering. At this distance, even large flaws may escape undetected, and tomographical techniques may become inapplicable.

2.2 *Tube material*

While plastic access tubes offer installation convenience, they may undergo debonding (separation from the concrete) with time. This phenomenon is noticed especially close to the top. As a result, testing carried out in such tubes may exhibit anomalies that have nothing to do with concrete quality. It has been suggested that this phenomenon can be mitigated by roughening the outside of the tubes and by filling them with water prior to concreting. Although the use of plastic tubes must not be ruled out, they should be used with caution. Steel tubes, by comparison, generally exhibit good contact with concrete and may save misunderstanding when test results are examined.

For single-hole testing, the use of plastic tubes as demanded by ASTM is mandatory. In this case, testing should be carried out as early as possible.

3 EQUIPMENT PROPERTIES

3.1 *Emitter frequency*

To detect an inferior material inclusion of dimension d, it should be much larger than the wavelength λ (Santamarina et al. 2001). The emitter frequency specified by the various Standards varies between 20 kHz and 100 kHz. Table 1 lists the prescribed frequencies with the respective wavelengths and size of the smallest detectable inclusion:

Table 1: Detectable inclusion

Emitter frequency (kHz)	20	30	50	100
Wavelength λ (mm)*	210	140	84	42
Detection threshold (mm)**	420	280	168	84

* - Based on a typical P-wave velocity of 4,200 m/s

** - Assuming $d > 2\lambda$

If, as we mentioned above, we aim at the 400 mm detection threshold, then the lower-end emitter frequencies allowed by the Standards, are acceptable. The higher end frequency, on the other hand, produces wavelengths approaching the size of individual aggregates and causing high attenuation. From our experience, frequencies in the order of 50 to 60 kHz combine long range with good resolving power.

3.2 *Depth measurement accuracy*

A ratio of 5:1 exists between accuracies required by ASTM and French standard. From our experience, current depth encoders are capable of the 0.2% accuracy or 50 mm required by the French Standard. However, since the size of detectable inclusions is much larger than these values, this accuracy seems unnecessary. Moreover, under typical site conditions reference levels (tube stickup or concrete surface) are also not very accurately defined. We may conclude, therefore, that the depth measurement accuracy may be relaxed and 0.5% or 100 mm (the larger of the two) seems a practical compromise.

3.3 *Time measurement accuracy*

As we have stated above, an emitter frequency of 50 to 60 kHz. is optimal for ultrasonic pile testing. According to the Nyquist–Shannon sampling theorem (Gaydecki 2004), exact reconstruction of a continuous-time band limited signal from its samples is possible if the sampling frequency is greater than twice the highest frequency component of the signal. Accordingly, for an emitter frequency of 100 kHz a sampling rate of 250 kHz should be totally adequate. Anything beyond that produces oversampling which carries its price in the form of larger, more cumbersome files and brings marginal benefit, if any.

Analysis of the error factors involved in cross hole testing (Amir et al. 2004) has proven that the uncertainty in FAT determination is 10% of the FAT value plus 27 μs. With this in view, it is unclear why the French and Chinese Standards demand a time measurement accuracy of 1 μs or even 0.5 μs. Such accuracy is of theoretical interest only and has no practical justification.

4 ANALYSIS OF THE RESULTS

4.1 *FAT picking*

Effective FAT picking is not a simple task, especially with noisy signals. When the number of pulses to be inspected is small, the task can be best done manually using some judgment. Since pile testing produces many thousands of pulses, manual FAT picking is not a practical proposition and the task must be performed by a suitable algorithm. Except for the CHUM Automatic FAT picking described by Amir & Amir (1998), all existing algorithms have to be fed by one or more parameters.

Among documents that we examined for this work, the French Standard prescribes a complex procedure for FAT picking. In essence, the first period is defined as the one in which the amplitude exceeds 0.05 times the maximum amplitude A_{max} of the whole profile (A_{max} is FAT-dependent as discussed below). This is basically “fixed threshold” algorithm, with the threshold level set automatically by each profile’s A_{max}. Our experience has proven that this algorithm never performs well.

The main weakness in the French approach is the interdependence of FAT and amplitude which we would prefer to see as two separate parameters. It also complicates the calculations since they have to be done by iterations. Other drawbacks are related to tomography, since oblique readings have a longer distance and weaker energy and may be wrongly classified as defects when compared to the stronger horizontal pulses of the same profile.

Both ASTM and the Chinese Standard keep silent as to FAT picking method, and leave it to the discretion of the equipment manufacturers.

4.2 *Signal amplitude*

Besides FAT, signal energy or amplitude can serve as a meaningful flaw predictor. The French Standard defines this parameter as the mean absolute amplitude of first 10 cycles following FAT. In the Chinese Standard it is defined as the peak voltage of the first cycle. Both approaches have their drawbacks: in the French Standard both FAT and energy are interdependent and have to be determined by an iterative process. The Chinese suggestion of taking the amplitude of the first cycle is even more problematic: deciding which cycle is the first one depends on the FAT selected, while the amplitude of the first cycle is often not representative of the whole pulse. ASTM leaves the definition of energy to the equipment manufacturers.

ASTM also keeps silent with regard to the accuracy of amplitude measurement. The French Standard sets the allowable error at 10% of the maximum, and the Chinese Standard to a relative error of 5%. When viewed against the anomaly definition of these documents (an amplitude drop of 80% and 50%, respectively) these criteria look reasonable.

4.3 *Noise*

Excessive noise (electronic and other) can seriously limit the maximum usable range between probes.

From our experience with the STA/LTA algorithm for FAT picking (Allen 1982), an STA/LTA threshold ratio between 2 and 3 gives satisfactory FAT picking in cross hole testing. This means that where noise exceeds one third of the amplitude of the first cycle, accurate FAT picking is not possible. Where noise is larger than the maximum pulse amplitude, FAT cannot be determined at all.

Considering this, it is not clear why none of the three Standards addresses this issue.

4.4 *Calibration and verification*

For any testing system, the need (or lack of it) for calibration and verification should be clearly stated. While ASTM does not address this issue, the other two Standards dictate the necessity to measure the "dead" time of the system. This "dead" time may be an intrinsic property of the system, which may be found by determining FAT in either air or water at predetermined transducer spacings and extrapolating the graph obtained back to zero distance. Another contributing factor is the delay time caused by the access tubes and the water inside. Amir et al. (2004)

measured this delay time for a particular case and got a result of about 20 μs.

Depth encoders used in the system should be calibrated when replaced or refurbished, and whenever there is a dispute on site regarding the accuracy of the measured depth.

4.5 *Anomaly definition*

Admittedly, test Standards are supposed to specify both the properties of the testing equipment and the procedures to be followed. The question whether Standards should also address interpretation is open for discussion.

Both French and Chinese Standards set down rigid rules as to what constitutes an anomaly, based on the analysis of both FAT and energy values. Such a mechanistic approach that disregards other factors may be abused by unqualified personnel. One should never forget that anomalies may result from factors not related to the pile proper, such as tube debonding, tubes out of parallel and dry tubes.

In view of the complexity involved in producing bored piles, and since rigid rules often fail under special circumstances, we prefer the ASTM approach which advocates that "interpretation (therefore) must contain proper engineering judgment and experience. Any evaluation of integrity is to be made by an engineer with specialized experience in this field, and is beyond the scope of this standard".

CONCLUSIONS

- The number of access tubes per pile should be not less than one per each 300 mm of diameter.
- Steel tubes, 50 mm diameter, should be preferred unless single-hole testing is performed in which case plastic tubes should be used.
- For best performance, the emitter frequency should be in the order of 50 to 60 kHz.
- Depth measurement accuracy should be 0.5% or 100 mm – the larger of the two.
- Sampling rate of 250 kHz is fully satisfactory for the above mentioned emitter frequency range.
- Rules for establishing FAT and energy should be simple, automatic and independent of each other.
- Standard should limit maximum noise to ensure sufficient range and accurate determination of first arrival.
- The definition of what constitutes an anomaly should preferably be omitted from the Standard and provided in the specification of the project.
- In the third millennium, with free international traffic of equipment and testing laboratories, national Standards should be replaced by globally accepted ones. With contributions by experts from around the world, ASTM International appears to be the most appropriate body to face this challenge.

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APPENDIX A - SUMMARY TABLE

Table 2 - Overview of subject dealt with in the Standards

Item	French	Chinese	ASTM	Suggested
Preparation for testing				
Number of access tubes	If D≤600 mm – two If 600<D≤1.2 m – three If D>1.2m – four or more Tube spacing – 0.3 – 1.5 m	If D≤800 mm – two If 800<D≤2m – three If D>2m - four	If D≤1 m – three If D>1 m – one per 250 to 300 mm of diameter	If D≤1 m – three If D>1 m – one per 250 to 300 mm of diameter
Tube material	Steel	-	Steel or plastic	Steel for cross, plastic for single- hole
Inner tube diameter (mm)	> 40	50-60	Typically 38-50	40-60
Dummy testing	Required	-	Required	Required
Functional inspection	-	-	Required	Required
Power and gain setting	Required	-	If necessary	If necessary
Calibration/verification	"dead" time calibration, semi-annual verification	System delay time	-	
Instrument specification				
Emitter voltage (V)	-	200-1000	-	Not specified
Emitter frequency (kHz)	20-100	30-50	30-100	40-100
Depth measurement accuracy	0.2% or 50 mm	-	1% or 250mm	1% or 50 mm
Time base accuracy	1 μs or 2%	0.5 μs	2 μs	2 μs
Amplitude accuracy	10% of maximum	5% of maximum	-	10%
Testing Procedure				
Cross hole	Bottom to top	-	Usually bottom to top	Bottom to top
Single hole	-	-	Described	Specify
Tomography	-	-	Hinted	Specify
Vertical spacing between pulses	≤ 10 mm	≤ 250 mm	≤ 50 mm	10-100 mm, 50 mm recommended for routine testing
FAT picking	Special algorithm	Not defined	Not defined	Automatic w/o user input
Energy calculation	Mean absolute value of first 10 cycles	Peak voltage of 1^{st} cycle	Not defined	Total energy off all captured signal from time=0
Presentation of results				
FAT or wave speed	FAT vs. depth	Wave speed vs. depth	FAT or wave speed vs. depth	FAT (μs) vs. depth
Energy or amplitude	Fraction of maximum vs. depth	Amplitude vs. depth	Relative energy or attenuation vs. depth	Attenuation (in dB)
"Waterfall"	Option	-	Required when using filter	Optional
Auxiliary parameters	-	Frequency, PSD	-	-
Anomaly definition	velocity and energy reduction	velocity and energy reduction	Not defined	Leave to project specification