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ACCEPTANCE CRITERIA FOR BORED PILES BY ULTRASONIC TESTING

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ABSTRACT

Ultrasonic testing, or crosshole logging (CSL), has become the primary means for judging the integrity of bored piles and barrettes. While the test procedure is now well standardized, interpretation of the results is still controversial. The following paper reviews a number of published criteria, and then goes on to evaluate the various sources of measurement error: Concrete variability, access tube effect, FAT picking error, sampling error and hardening time effect. It is shown that in certain cases, especially in smaller diameter piles, potential error may exceed some established acceptance criteria.

The paper describes two methods for accurate determination of wave velocity, and suggests themes for further study.

1. INTRODUCTION

Ultrasonic testing, or crosshole logging (CSL), is now a widespread means for evaluating the integrity of bored piles. In many specifications, anomalies observed in the ultrasonic test results are a sufficient reason to reject a pile. Nevertheless, the definition of what constitutes an anomaly is in many cases vague. The main reason for this is the fact that, until recently, available testing systems have not permitted a detailed error analysis. This paper is intended to shed light on this subject and to suggest criteria for defining an anomaly.

The present study, carried out with modern logging equipment, points to several factors that may influence CSL test results. Some of these can be eliminated by applying due care. Other factors, such as air voids around the access tubes, inhibit testing altogether and therefore do not count. The main sources for error that were identified are:

- Normal variability of concrete properties
- Wave propagation inside the access tubes
- Sampling error
- Fat picking error
- Concrete hardening rate

2. EXISTING ANOMALY DEFINITIONS

England (Turner, 1997) investigated the factors influencing CSL results, and came to the conclusion that an increase of 15 to 20 percents in the First Arrival Time (FAT) warrants further investigation. Since then, several bodies have produced their own anomaly definition

The Federal Highway Administration (FHWA) published its own concrete rating criteria, based solely on wave velocity. When the velocity reduction is 10% to 25% the concrete rating is defined as "questionable", while a larger reduction characterizes poor quality or contaminated concrete.

California Department of Transportation (Caltrans) bases its classification on both FAT and pulse shape and amplitude. To qualify as a "significant anomaly" a pulse must show:

- Severe signal distortion
- Much lower signal amplitude
- An increase in signal arrival time of 20% or more

These rules, however, do not provide a clear reference value to which the results should be compared nor do they consider the affect of construction (e.g., drilling, concreting and ground conditions).

The Chinese Standard for crosshole ultrasonic testing (Chen Fang et al., 2003) bases acceptability mainly on deviation in the wave velocity. In this document, the reference velocity is defined as follows: all recorded velocities in a given profile are sorted in decreasing order. First, a number of low velocity points below an arbitrary cutoff value are disregarded. The mean V_m and standard deviation σ are then calculated for the remaining points. If $V_0 = V_m - \lambda.\sigma$ is below the cutoff value, it is defined as the reference velocity V_c. All points with velocities smaller than V_c are considered anomalous. λ is a number between 1.64 and 2.69, depending on the number of data points analyzed.

Another criterion for defining an anomaly is attenuation. Any point at which amplitude attenuation exceeds the mean attenuation by more than 6 dB is considered anomalous. Two additional criteria, defined as auxiliary, are PSD (which is a geometrical criterion) and dominant frequency of the recorded pulses.

3. SOURCES OF ERROR

3.1. Concrete Variability

A statistical analysis was carried out on the crushing strength of 372 samples of 30 MPa concrete, supplied by a modern mixing plant to a large piling project in Israel. Each sample contained six cubes, three of which were tested after seven days and the other three after 28 days. The test results are summarized in Table 1.

Table 1: Concrete statistical data

Concrete age	7 days	28 days
Maximum strength (MPa)	54	69.5
Minimum Strength (MPa)	22	29
Mean strength (MPa)	38.24	49.55
Standard deviation (MPa)	6.12	6.59
Coefficient of variation (%)	16	13

The results indicate that, although with time it may become somewhat more uniform, concrete strength is still a rather heterogeneous property reflecting the variability of concrete batching.

In the example given above, concrete that is weaker than the mean by 3σ (three standard deviations) still has the acceptable 30 MPa strength. Thus, at an age of seven days, concrete strength at any point may be as low as 3x16% = 48% below the mean. Incidentally, the 3σ figure was also adopted by California Department of Transportation (Caltrans) in its acceptance criterion based on the radioactive test method (O'Neill & Reese 1999 p. 500).

Wave velocity c is related to cube crushing strength f_c by the following equation (Amir 1988):

$$c = K.f_c^{1/6} \qquad \text{(Equation 1)}$$

in which K is a dimensional constant. This relationship is similar to results published by Davis & Robertson (1975) – (Figure 1)

Since ultrasonic testing is mostly carried out around the age of seven days, the allowable 48 percent decrease in concrete strength translates through Equation 1 into an allowable ten percent drop in the wave velocity (or increase in arrival time).

3.2. Access Tube Effect

Access tubes used for crosshole testing may in practice have any diameter D between 40 mm and 100 mm (1.5 to 4 inches). Probes with an outside diameter of 25 mm, which are widely in use, may move laterally inside these tubes during the test. The extra travel time in water (wave velocity of 1.5 mm/µsec) may vary between zero and Δt, where:

$$\Delta t(\mu s) = 2\frac{D-25}{1.5} \qquad \text{Equation 2}$$

Where D is expressed in mm. Thus, the variation in FAT due to this factor may be anything from 20 μsec (for 40 mm tubes) to 47 μsec (for 60 mm tubes), and the importance of this factor is immediately evident. Fortunately, it can be controlled to a certain degree by using flexible spacers that would keep the probes centered while not hampering free movement. As an estimate, careful use of such devices could limit the in-tube tolerance to around 10 mm, equivalent to 13 μsec in terms of FAT.

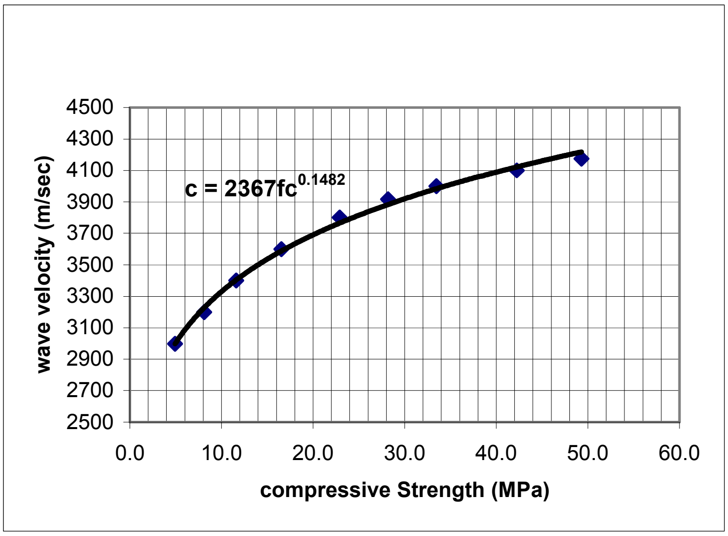

Figure 1: Wave velocity as a function of cube strength (after Davis & Robertson 1975)

3.3. Fat Picking Error

First Arrival Time (FAT) is an arbitrary, rather than deterministic entity (Amir & Amir 1999). The ultrasonic emitter produces a short pulse, which propagates in the surrounding medium and is eventually intercepted by the receiver. In an absolutely homogeneous medium, such as water, waves travel in straight paths (rays) and the recorded pulse will consist of a sharp rise and a few cycles before it dies out (Figure. 2). FAT in such a case is easily identifiable. In comparison, waves in concrete will as a rule propagate in curved paths rather than in straight lines (Santamarina et al. 2001). As a consequence, any given pulse recorded by the instrument is a superposition of numerous wave paths. The shape of the pulse is thus a function of the relative FAT and energy of each contributing wave path. In many cases, a pulse will assume a fan shape in which it is difficult to pick a unique FAT (Figure 2). Different algorithms used for this purpose may give different FAT values, depending both on the algorithm employed and on the parameters selected by the operator. For typical pulses, the error caused by this factor alone can be 10 μs or more. Thus, this factor can be of utmost importance in relatively small piles.

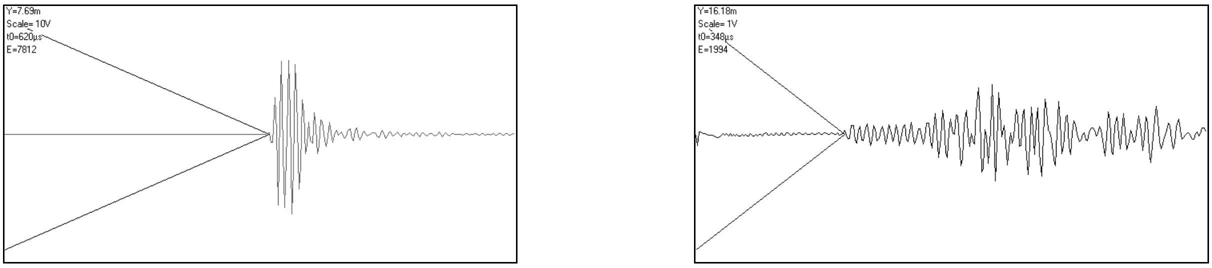

Figure 2: An ultrasonic pulse obtained in water (left) and in concrete (right)

3.4. Sampling Error

According to ASTM (2002), the minimum sampling rate in crosshole testing shall be 250 kHz. This implies a sampling error that can be as large as 4 µs.

3.5. Total Error

The total error in FAT readings is an algebraic sum of the above items, giving 10% of the reading plus 27 µsec. Figure. 3 shows the importance of this error in short range testing. The bold lines represent the FHWA limits for questionable concrete (10 to 25 percent). Obviously, perfectly acceptable concrete may fall into this category. Furthermore, for small tube spacings a concrete may be classified as “poor” on the basis of normal test results.

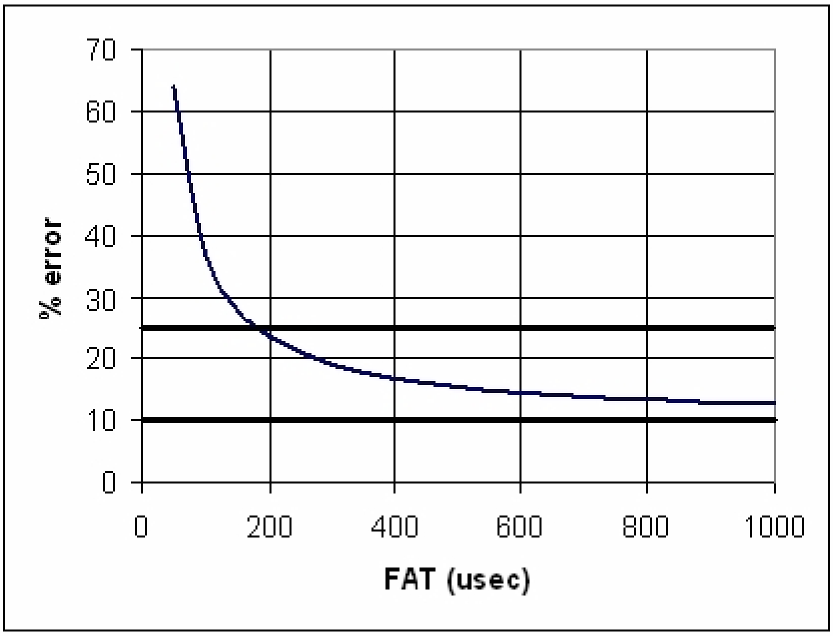

Figure 3: Maximum error vs. FAT

3.6. Hardening Time Effects

Experience has shown that, beyond the basic factors contributing to the total error, concrete hardening rate plays a major role in the CSL results obtained. In a large-diameter pile, containing concrete from numerous batches, small differences in retarder contents will cause different zones in the pile to harden at different rates. Ultrasonic logging of such a pile may show serious anomalies. A study of several case histories (Figure 4) shows that such anomalies may just disappear in a retest after several weeks of additional curing.

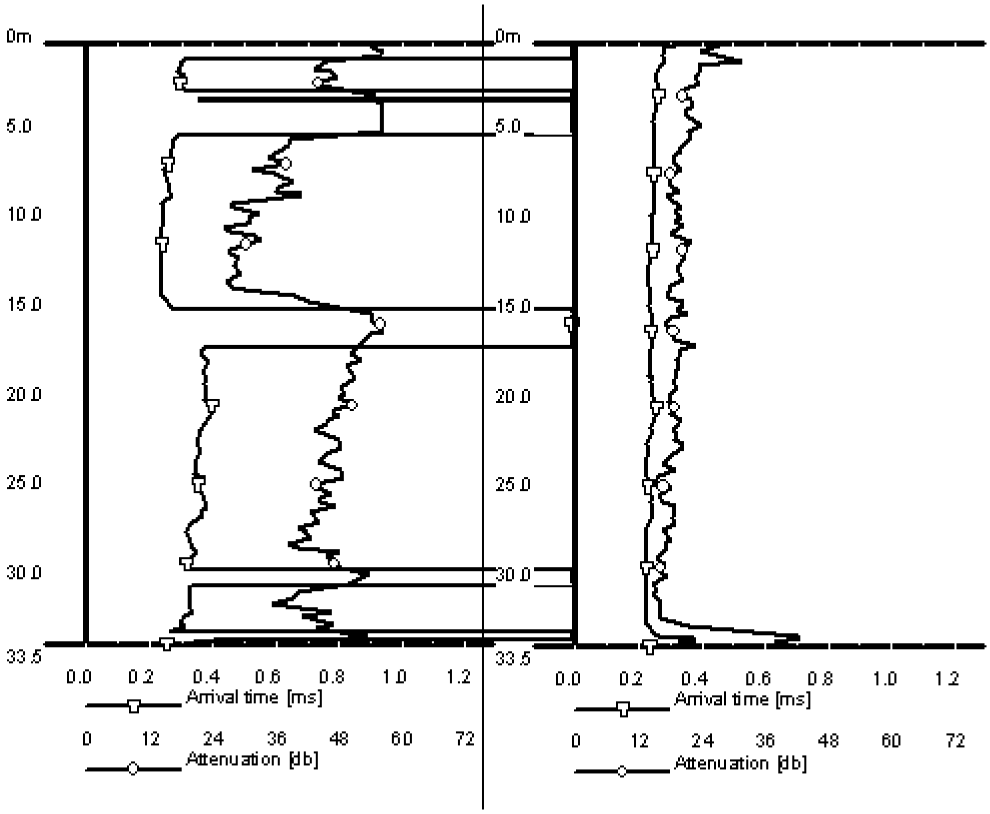

Figure 4: A profile with serious anomalies (left), retested six weeks later (right)

4. WAVE VELOCITY AS AN ACCEPTANCE CRITERION

To the structural engineer, wave velocity has no intrinsic meaning. It is useful only to the degree it can serve as a predictor of concrete crushing strength. However, due to the special correlation between wave velocity and concrete strength (Equation 1), a small change in wave velocity may reflect a major change in concrete strength. Thus, every effort should be made to extract the "true" wave velocity from the crosshole test results.

Due to the specific test setup, waves created by the vibrations inside the emitter take a certain time to pass through the emitter itself, the surrounding water and the tube wall. Unless this factor is taken into account, the velocity calculated by simple division of tube spacing by the FAT (the "apparent" velocity) can be misleading. This factor can be extracted in two ways:

- Comparing results from different tube spacings

- Analyzing oblique readings.

The first method may be illuminated by results from crosshole tests run on a large-diameter bored pile. This pile, 2.44 m in diameter and 18 m deep, was equipped with eight access tubes. 23 out of the possible 28 profiles were logged, and the tube spacings (center-to-center) were noted. The mean FAT for each profile was then calculated and plotted against the respective spacing. The results (Figure. 5) show a clear linear relationship with a slope ("true" velocity) of 4,532.6 m/sec and an offset of 90.7 mm. This means that for calculating the "true" velocity, all tube spacings have to be increased by this amount. The effect of this offset may be extremely important for smaller diameter piles and shorter tube spacings.

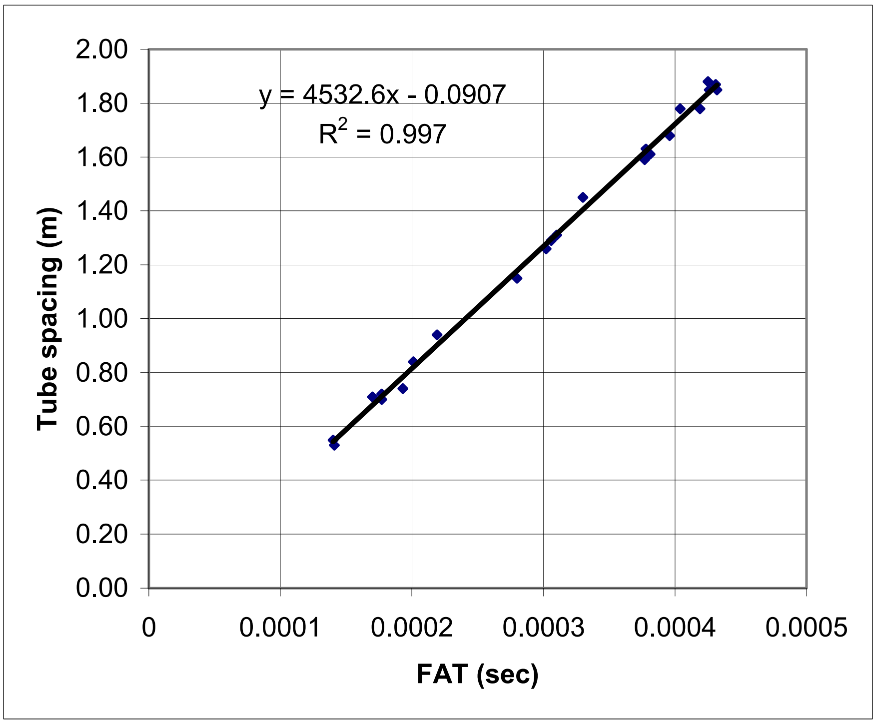

Figure 5: FAT vs. tube spacing in pile Q2

For the second method, a special crosshole profile is logged with one transducer held stationary and the other one pulled until signal strength becomes so low that FAT picking is impossible.

The results of such a test (Figure 6) typically show a straight section between an upper and a lower curved part. When the oblique distances between the probes are analyzed versus the FATs obtained in this straight section, the slope obtained is equal to the "true" wave velocity. This method has the advantage of producing immediate results, and can be applied even when all spacings are equal or similar.

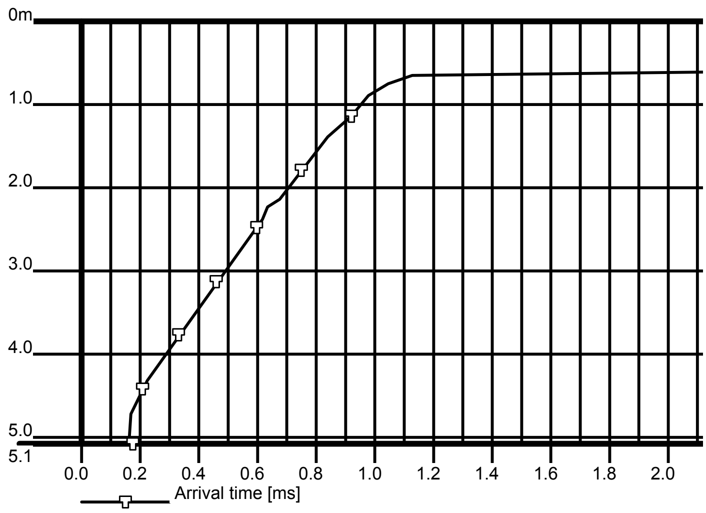

Figure 6: Oblique test results

CONCLUSIONS

- Even under tight control, concrete properties will show a large scatter that will have a material influence on the results of the crosshole ultrasonic test.
- In large diameter piles, different zones may harden at different rates. Therefore, apparent anomalies may shrink or even disappear on later retest.
- Access tubes with the smallest practicable diameter should be specified. When circumstances dictate oversize tubes, special spacers have to be devised.
- Due to the scatter in concrete properties and test limitations, the total error in reported FAT may by in the order of 10% plus 27 μsec. For tube spacings of 800 mm or less, existing acceptance criteria may thus be difficult to meet.
- Wave velocity is a useful predictor of concrete strength, provided it is measured rigorously. The oblique method of wave velocity determination is both simple and accurate.
- Due to the unavoidable scatter in FAT values, it should not be used as a sole acceptance criterion; On the other hand, the Chinese 6 dB limit appears to be too severe.
- The dominant frequency approach shows promise as an auxiliary predictor, and more research should be initiated in this direction.

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