Application of Stress-Wave Theory to Piles, Niyama & Beim (eds) © *2000 Balkema, Rotterdam, ISBN 90 5809 150 3*

Pile testing competitions – A critical review

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ABSTRACT: A number of pile testing competitions, using low-strain techniques, took place in different countries between 1987 and 1996 and soon started heated debates by the professional community. Since the outcome of these competitions was obviously contentious, they do deserve a critical review. Such a review may serve as a basis for more productive competitions in the future. These, in turn, will highlight both capabilities and limitations of existing methods and contribute to the advancement of new techniques.

The authors describe for each competition the testing scope and program, piles tested, the nature of the defects installed, the participating parties, and the results obtained. They go on to analyze each competition, specifically stressing those items that if done differently could have significantly improved the outcome. Based on the lessons learned from these events, the authors present ground rules for future pile-testing competitions. In addition, the importance of organizing competitions also in downhole testing applications is strongly recommended.

1 INTRODUCTION

In spite of the rapid progress in piling techniques (and maybe because of it), defective piles and drilled-shafts are still encountered at many construction sites. Among all the methods designed to test the integrity of bored piles, only two have proved to be of real practical value: The sonic (echo) and the ultrasonic (cross-hole) methods.

The sonic method was first applied a quarter of a century ago (Steinbach and Vey 1975). Since then, it has established itself as the leading method for testing the integrity of all kinds of piles. With the advent of handheld computing, sonic testing has become more reliable and at the same time more affordable.

The sonic method is based on pressing a sensor against the surface of the pile head while hitting the surface with a hammer. The hammer blow creates a low-strain wave that travels down the pile and is reflected from the pile toe, as well as from any abrupt change in the pile impedance. The hammer may be either plain or instrumented, and the results may be analyzed and presented in either time or frequency domain. An extensive treatment of the sonic method is presented by Turner (1997). The popularity of the method has brought a proliferation of both instrumentation and testing laboratories. Consequently, it naturally became a subject for competition.

2 PILE TESTING COMPETITIONS

2.1 *Objectives*

In principle, pile-testing competitions should be held with the some or all of the following objectives in mind:

1. Kindling the competitive spirit amongst developers, manufacturers, and users of equipment
2. Establishing the actual (as opposed to claimed) capabilities and limitations of the method
3. Indicating where advances in the state of the art are required.
4. Serving as milestones to monitor progress in both instrumentation and analysis tools
5. Providing an opportunity for potential clients to obtain reliable comparative data regarding the performance of available instruments

3 COMPETITION OVERVIEW

Following is a brief summary of five such competitions, held in Belgium, The Netherlands, and the USA (three of them), respectively.

3.1 *Ghent 1987*

The first known integrity testing competition was held in Ghent, Belgium in 1987 (De Jaeger et al. 1987). The Belgian Society for Soil Mechanics and foundation engineering organized this event. Altogether, the twenty test piles were constructed by four different methods, five piles each:

1. Atlas helicoidal (sawtooth profile) piles, diameter 430/530 mm
2. De Waal precast concrete driven piles, 320x320 mm
3. Socofonda CFA piles, diameter 460 mm
4. Fundex piles, bored with rotated casing and cast in situ , diameter 390 mm

The five testing firms that participated were given the pile diameters, and told that the pile lengths range between 11 m and 16 m. No defects were knowingly produced, and the task in hand was to determine the correct length.

The best overall length agreements were obtained in the Socofonda and Fundex piles. The lengths obtained for the Socofonda piles were 93% and 100% of the correct lengths. For the Fundex piles, the spread was between 94% and 102%. Such results are perfectly acceptable. On the other hand, poor results were reported for the precast piles (82% to 120%) and the Atlas piles (101% to 125% for three of the piles, with no results at all for the other two). The testing of the Atlas piles also produced poor results. Although the Atlas piles had the lowest L/D ratio (26 to 30), all testers reported lengths that were too high.

The conclusions from this exercise are as follows:

1. The precast driven piles were difficult to test both due to higher shaft resistance and to having the highest L/D ratio (41 to 53).
2. The testers of the Atlas piles probably neglected the fact that a helicoidal pile exhibits a wave velocity that appears to be much lower than that of a straight-shafted pile (Vyncke and van Nieuwenburg 1987).
3. The CFA piles and the Fundex piles were the easiest to test. This is probably due to their lower L/D ratios (32 to 37) as opposed to the precast piles.

3.2 *California 1990*

The California test program was carried out in the framework of a research project for the Federal Highway Administration (Baker et al. 1993). It took place on two sites: Cupertino, with dry gravelly and sandy soil and San Jose, with clayey soil under groundwater. The piles had a nominal diameter of 915 mm and lengths of between 7.6 m and 18.9 m.

There were five participants in the program, applying four testing methods: Sonic echo (time domain), transient dynamic response (frequency domain), cross-hole (ultrasonic) and radioactive (gamma-gamma). All the participants were provided in advance with the lengths and shapes of the piles that they were to test.

3.3 *Texas 1990*

The Texas test program was a continuation of the FHWA project (Baker et al. 1993). Altogether, nine bored piles were constructed, seven of which had known irregularities. All piles had a nominal diameter of 915 mm, with lengths varying between 11 m and 24 m (L/D ratios between 12 and 26).

The irregularities were of different character and magnitude. Four of the piles had a single planned necking at a depth of between 3 and 18 m, the reduction in cross section being between 12 and 50 percent. Three other piles had both increased and decreased cross sections at various depths. In addition to the planned defects, some unplanned defects occurred and were recorded during construction.

Five testing firms took part in this competition. The testing firms received full information regarding the subsurface conditions, as well as the lengths of the two reference piles. No further data about the existence of defects was divulged.

The tests were conducted in two stages: In stage one, only surface (sonic) methods were used. In stage two, the contestants were allowed to lower testing equipment into access tubes which were prepared beforehand.

The results of the Texas program may be summarized as follows:

1. At depths smaller than 7 m below the top of the pile head, 80 percent or more of the testing firms managed to identify all important defects in the cross section.
2. The success rate dropped to 60 percent at a depth of 9 m.
3. All participants failed when the defect (necking) was located at a depth of 18 m.
4. Even at shallow depths, participants failed when the reduction in cross section area was merely 12 percent.
5. In general, an enlarged cross-section was more difficult to find than a reduced one.
6. The participants had difficulty in determining the length of the pile when there was a major necking at mid-length, or when a defect existed near the toe of a long pile.
7. As expected, no participant could identify a "soft bottom" condition.

3.4 *Delft 1992*

The Delft competition took place in conjunction with the Fourth International Conference on the Application of Stress-Wave Theory to Piles (Smits 1996). Twelve laboratories, employing six different types of instruments, participated in the event. The testing objects in this case were rather uncommon: All of the ten test piles were made from precast concrete and installed in the following way: First, closed-end steel tubes were driven to a predetermined depth. Then, a thin bed of sand was placed at the bottom of the tubes and the precast piles were lowered into the empty tubes and placed on the sand-bed. The space around the piles was then filled with a bentonite-cement mixture supposed to represent the local soil stiffness.

The test piles had a nominal cross-section 250-mm square. Two piles were straight shafted, with respective lengths of 17 m and 18 m. Of the rest, six piles were produced with the cross-section along a given length either enlarged to 300 mm. square or reduced to 200 mm square, or both. The two remaining piles had a sawed notch, 10 mm. thick and occupying one half of the cross section. Similar notches were also produced in two of the piles with enlarged section.

The testing circumstances were also noteworthy, in two important respects: First, the participants were not allowed to approach the piles, and the notary public's clerk was mobilized to hit the piles with the hammer. Second, the participants were given beforehand the exact shapes of all the piles, and their task was to decided which of these shapes best fits each of the reflectograms they obtained.

All the participants managed to achieve was a correct fit for between three and seven piles, with a mean success rate of 44%. The scores for the individual piles varied between zero (straight shaft, L = 18m) to 100% (straight shaft, L= 17m).

3.5 *Texas 1996*

This competition (Samman and O'Neill 1997) took place on the campus of the University of Houston, Texas. Altogether, twenty-two piles were tested. Eleven of the piles had a diameter of 460 mm and were bored to a depth of 4.6 m. The other eleven piles were 760 mm in diameter and 7 m long in the ground. Some of the piles were constructed with polymer slurry while the rest were cast in the dry. Six of the piles were regular piles, while sixteen piles had planned built-in defects. These defects were produced from 25 mm thick soft rubber mats, laid horizontally. The mats were placed at different depths, but not more than one per pile. Each occupied between 10 and 50 percent of the total cross section of the pile.

Eight laboratories took part: Two were from government agencies, five were commercial and one academic. The contestants were asked to report for each pile whether it is sound or defective, and, in the latter case, specify the depth and severity of the defects. The participants were to submit two reports: A preliminary report on the same day, and a final report within five days.

The results, as can be expected, were far from satisfactory: In the piles intended to be sound, only 7% of the tests confirmed the integrity. In the anomalous piles, 82 % of the defects were found. These rates improved somewhat in the final reports, to 25% and 83%, respectively. The success rate for the defective piles may seem impressive, but a deeper look into the matter is far less encouraging: Of all the reported defects, only 36% managed to fit the depth of the defects within ±20 percent. Of these, only 37% provided the size of the defects within ±20 percentage points. On the other hand, the participants reported on the average 1.3 "phantom", i.e. nonexistent, defects per pile. None of the contestants, or the testing instruments used, demonstrated a markedly outstanding performance.

4 EVALUATION

4.1 *Ghent 1987*

The organizers declared that the piles were between 11 m and 16 m long. Thus, a tester who would have reported a uniform length of 13.5 m (the mean of the above limits) for all the piles would be accurate to within ±10% in 90% of the piles.

While highlighting the influence of construction method on testability, the Ghent competition totally neglected the most important purpose of sonic testing -- finding defects!

Publication of the test results was very complete, and included a special seminar where the results were presented and discussed.

4.2 *California 1990*

Since the organizers of the California testing program gave the participants full details regarding the planned defects, success rates have no meaning. It is therefore questionable whether the California test may qualify as a competition and therefore the case is not pertinent to the present paper. (The results are of course interesting in other contexts).

4.3 *Texas 1990*

While in California, the participants were given information beyond that normally provided to testers, in Texas they got too little. When a pile testing firm is invited to a construction site, it is customary and necessary to provide it with all relevant information, such as soil data, pile construction records and piling logs with the as-made length and details of any irregular events that may have happened. Testing under the "Texas rules", with no a-priori knowledge of the pile length, is therefore the exception and detracts from the effectiveness of the results.

In other respects, the planning and execution of the Texas tests was very effective. The tasks were well graded from easy through difficult to impossible. Thus, the performance of contemporary systems was well defined. This competition proved convincingly that the sonic method is a viable technique for investigating pile integrity. It showed that sonic equipment is able to identify most important defects where they matter most, that is in the upper part of the pile. On the other hand, it demonstrated that the sonic method is unable to distinguish features that are relatively small or located deep down the pile.

4.4 *Delft 1992*

As expected, the Delft 1992 event triggered a lengthy debate in Ground Engineering magazine (Stain 1993, 1993a, Ellway 1993). The main criticism was aimed at the following points:

1. Most routine sonic testing is done on cast in situ piles, with an inherent variability of both concrete quality and shaft resistance soil friction and a rough top surface. Precast piles in an artificial "soil" with smooth tops thus cannot do not represent real-world life conditions.
2. The unusually high L/D ratio (72) is generally considered to be beyond normal testing limits.
3. Most of the anomalies, and especially the saw cuts, were outside the theoretical performance envelope of the sonic method.
4. Actual testing was performed by inexperienced people, not familiar with fine points of the test.

In all important respects, the Delft competition did little to advance the state of the art, and in fact was a large backward step from the Ghent affair. With the whole setup being detached from the real testing world, it had only reinforced the (erroneous) belief that sonic testing is not to be taken seriously, being based on little more than guesswork.

4.5 *Texas 1996*

In view of the poor results obtained in Houston 1996, the organizers declared that sonic testing "may not be reliable enough to be regarded as a stand-alone measure of the assurance of drilled shafts". Could it be that not the sonic method was to blame, but the organization of the competition? In principle, the Houston competition had the correct ingredients to simulate a realistic testing assignment. The main factor that detracted from the success of this competition lay in the nature of the "defects": To be applicable, the sonic method utilizes a wavelength that is large in comparison with the pile diameter. A defect with a vertical dimension of 25 mm is therefore well beyond the capability of the sonic method unless it occupies all (or almost all) of the cross section of the pile. Since the defects in Houston occupied at most one half of the total pile area, it took a lot of good luck to discover any of them. The fact that some defects were placed as close as 300 mm to the top only made things worse. Moreover, a rubber sheet, such as that used to model cracks in the piles, has a low stiffness when unstressed. In contrast, a rubber sheet stressed by the weight of the concrete has a considerable larger stiffness that does not deviate enough from the stiffness of the concrete. It would be have been very hard to detect a reflection from the rubber sheet.

Since most competitors were keen to find defects, and the nature of the defects made them practically undetectable, the competitors found defects even in perfectly good piles. This is the main explanation for the participants discovering defects also in the good piles (plain coin tossing would do markedly better!).

5 DOWNHOLE TESTING COMPETITIONS

Admittedly, the sonic method has a few basic flaws: First, the wavelength used is about 3 m, which provides rather poor resolution and second, both input (hammer blow) and output (accelerometer signal) are remote from potential defects. To overcome these drawbacks, the industry has developed instrumentation that is lowered into the pile through-access tubes.

Historically, access tubes were first used for testing piles with radioactive isotopes. This method is now fast disappearing due to its limited range, environmental limitations, and regulatory requirements. It was largely replaced by ultrasonic instrumentation, using wavelengths in the range of 50 mm to 100 mm. Modern ultrasonic equipment (Amir and Amir 1998) combines long range (~3m) with high resolution. With a suitable setup, it can also perform tomographical imaging and produce two-dimensional vertical sections. Another technique, still experimental (Samman and O'Neill 1997), utilizes clear plastic tubes and a downhole video camera.

In view of their obvious advantages, downhole testing of piles has become the preferred method in certain sectors such as bridges and high rise buildings. The time is ripe to organize suitably designed competitions which would greatly benefit the piling industry.

6 RULES FOR FUTURE COMPETITIONS

To be effective, competitions must satisfy certain minimum criteria. Based on the analysis of five such competitions, The following rules are therefore suggested:

1. The test program should be based on sound theoretical foundations – participants must not be asked to perform the impossible.

2. The tests should be carried out on real piles, conventionally constructed in real soil.
3. The piles should have different lengths and length-to-diameter ratios.
4. As a rule, organizers should create no more than one anomaly per pile.
5. Anomalies should be carefully designed and constructed to resemble, as far as possible, anomalies that are actually encountered in practice. This includes soil pockets and zones of weak, honeycombed concrete.
6. The anomalies should be of different magnitudes, with an importance ranging between minor irregularities to complete discontinuities.
7. Tests should be carried out by experienced personnel, familiar with the testing systems
8. Participants should be provided with normal testing conditions.
9. Pile heads should consist of reasonably good-quality concrete. Testers who desire to improve the surface must be given an opportunity to do so.
10. Participants should be provided with sufficient soil data (borehole logs) and pile data in the manner and to the extent usually provided to testers on actual construction projects. This includes the as-made lengths and any special events observed during construction.
11. Participants should not get any data regarding the special features installed in the piles.
12. In addition to the piles specially prepared for testing, the competitors must be given an opportunity, where possible, to test "ordinary" control piles at the same site.
13. The integrity of the piles should be investigated also by conventional methods, such as coring and pile extraction, in order to provide reference to both the integrity of the piles and the success of the integrity testing competition.
14. The competitions setup and program should be reviewed and sanctioned by a reputable international body, such as APTLY, the Alliance of Pile Testing Laboratories.

7 SUMMARY

Pile testing competitions represent a major technical and financial effort for organizers and competitors alike. To profit from this investment, these competitions should be planned very carefully. The experience accumulated from pile testing competitions in the past can serve as a good basis for planning successful competitions in the future. Such competitions should be open to all available testing methods, both commercial and experimental. Such events should be coordinated with APTLY and published in full in a technical journal or conference that is readily accessible to the general piling community.

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