A Review of International Standards' Guidance on High-Strain Dynamic Testing and Signal Matching of Pile Stress Wave Data

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ABSTRACT

High-strain stress wave data from vibratory or impact driving of a premanufactured pile or dynamic load testing of a premanufactured or cast-in-place pile can be subjected to signal matching. The term signal matching describes the process of "detailed matching of the stress wave data" (Fleming et al., 2009) typically performed using commercial software. The process involves discretizing the pile into a number of elements and the soil into layers, assigning initial values to the various parameters and iteratively adjusting the input parameters until an acceptable match is achieved with the measured signals. International standards such as Australian Standard AS2159 "Piling - design and installation", American Society for Testing and Materials ASTM D4945-17 "Standard method for high-strain dynamic testing of deep foundations" and International Standard ISO/FDIS 22477-4 "Geotechnical investigation and testing – testing of geotechnical structures – Part 4: Testing of piles dynamic load testing" address equipment requirements, the dynamic load test procedure and minimum reporting requirements. However, only ISO/FDIS 22477-4 provides discussion regarding the means of analysis, specifically signal matching. This paper will review the available guidance provided in the international standards on signal matching, and provide further considerations for signal matching, including the need for a sensitivity check and matching the signals to the displacement time history, and dynamic testing.

Keywords: high-strain dynamic testing, piles, signal matching, international standards

1 INTRODUCTION

At least three recognized international standards address equipment and reporting requirements, and testing procedure for high-strain dynamic testing of piles. These are the Australian Standard AS2159 "Piling - design and installation", American Society for Testing and Materials ASTM D4945-17 "Standard method for high-strain dynamic testing of deep foundations" and International Standard ISO/FDIS 22477 4 "Geotechnical investigation and testing – testing of geotechnical structures – Part 4: Testing of piles dynamic load testing." Only ISO/FDIS 22477-4 provides a discussion with respect to the means of analysis, specifically signal matching.

2 DEVELOPMENT OF THE METHOD AND STANDARDS

High-strain dynamic testing evolved over a period of time, with the development of the method taking place in parallel several parts of the world.

Estimation of the static resistance of piles subjected to dynamic loading was initially attempted using the pile driving formulas (Terzaghi, 1943). The formulas, which correlated the measured permanent set of a pile subjected to a known hammer weight and drop height to the soil resistance, included the use of over-simplified assumptions that proved to be deficient and unreliable.

According to Hertlein and Davis (2006), the first references to either the stress wave phenomena or measurement of high-strain stress waves in driven concrete piles were published in the 1930s in Australia (Isaacs, 1931) and the United Kingdom (Glanville, Grime, Fox and Davies, 1938).

It is believed that the first practical use of the technique involving measuring actual stress-wave in piles was in 1956 by The Netherlands Organisation (TNO) as reported by Verduin (1956).

In parallel in the United States, E.A.L. Smith of the Raymond Pile Driving Company built on the previous work of Isaacs to develop a practical numerical method for pile-driving analysis in the 1950s (Smith, 1960).

Smith's work was taken up by researchers at Texas A&M University where they developed a program to take advantage of the rising computing power that was becoming commercially available in the late 1960s (Lowery, Hirsh, Edwards, Coyle and Samson, 1969).

A separate research program started in 1964 at Case Institute of Technology (now Case Western Reserve University) in Cleveland, Ohio, USA that lead to the development of the Case Method, a closed-form solution used for rapid capacity assessment, and the signal matching software known as "Case Pile Wave Analysis Program (CAPWAP)". In CAPWAP, signal matching is carried out by matching the calculated and measured force signals. At about the same period, a parallel project in Europe resulted in the development of the TNO-Wave analysis method. Both methods are based on generally similar physical principles and can provide very similar results. However, in addition to some philosophical differences, there are some key differences in data processing and analysis.

With the maturing of the signal matching method, the American Society for Testing and Materials (ASTM) published the first standard for the test method in 1986. As would be expected, the original standard was heavily influenced by the state of practice in North America. The standard, D4945 "High Strain Dynamic Testing of Piles" helped bring about the subsequent widespread acceptance of the method in the US and elsewhere.

3 INTERNATIONAL STANDARDS

As mentioned above, the three referenced standards address equipment and reporting requirements, and testing procedure for high-strain dynamic testing of piles. In terms of guidance for data analysis, the standards vary considerably. In general, the three standards acknowledge means of analysis other than just signal matching. For instance, Appendix B of AS2159 notes that the report should include "any assumptions critical to the interpretation of results (e.g., damping factor)" and that "justification for such assumptions should be provided." For "rigorous analysis" which is inferred to mean signal matching, the AS2159 Standard notes that the report should include "the full results of such analyses and the following information: (i) Predicted pile head movement at the maximum serviceability limit state and at the maximum mobilized resistance. (ii) Shaft and end bearing components of the maximum mobilized resistance."

Similarly, item 7.3.6 of the most current version of ASTM (D4945-17) indicates that the report should include "analysis method(s) used to interpret or evaluate test measurements." The authors infer that this implies signal matching rather than the closed-form solutions that are reported during testing.

Different from AS2159 and ASTM D4945-17, ISO/FDIS 22477-4 actually acknowledges five means of analyses that include driving formula (Appendix A), wave equation analysis (Appendix B), closed form (Appendix D), signal matching (Appendix E) and multiple-blow dynamic testing technique (Appendix F). The ISO Standard includes specific requirements for each of the methods of analysis and describes the analysis method in detail in the listed appendices. The focus of this paper is on signal matching.

4 SIGNAL MATCHING

Annex E of ISO defines signal matching as "a procedure for compressive resistance evaluation from dynamic impact load testing. In the procedure pile and soil are modelled and parameters within the model are varied to make a match to measured signals. The sensitivity of the solution shall be checked by comparing the pile behaviour to soil or ground investigation information."

ISO further expands on signal matching by stating that "the force-time history…is applied as an action and the system response is calculated for the upward wave.". On the other hand, Piling Engineering (Fleming et. al, 2009) describes the "detailed matching of stress wave data" as an iterative process "where the soil parameters for each element down the pile are varied until an acceptable fit is obtained between measurements and computed results" and where "either the measured force signal or the measured velocity signal is used as an upper boundary condition in the computer model. The fit is then obtained in terms of the other variable."

Interestingly in the example included in Annex E is a comparison of the matches with the force and velocity traces.

ISO indicates that "by varying the input parameters, predominantly the soil or ground parameters (quake – the limit of elastic displacement, damping factors, stiffness of the springs and soil mass) the calculated curve is adapted to fit the measured curve. The calculated set is also compared to the measured set of the pile with each test blow." Given software capabilities, it could be argued that the Standard should be modified to recommend matching of the calculated and measured displacement time history curves rather than the calculated and measured permanent sets only.

With software programs such as PLAXIS, we are seeing several authors performing signal matching using transferred energy time history and also force versus pile head displacement. Once a reasonable match is obtained, the static and dynamic components of the shaft and pile toe resistances are separated to estimate the pile compressive resistance.

5 BACKGROUND INFORMATION FOR SIGNAL MATCHING

5.1 What ISO says

ISO notes that "the specific signal matching programme used will have a recommended range for the user defined input parameters, which should be used taking into account the local soil or ground conditions by comparison to soil or ground investigation data."

5.2 What should ISO say?

The key point of the statement in the previous section is "taking account" of other information. In the authors' opinion, signal matching should be guided by test boring logs, cone penetration test (CPT) and seismic cone penetration test (SCPT) logs, etc. Pile installation records should also be considered in the analysis. It is extremely important to know how the pile was installed. This would include all construction delays related to splicing, equipment breakdown, or stoppages due to safety or environmental reasons. In particular, signal matching should also consider the effects of vibratory installation for premanufactured piles.

Obviously, static loading test data should also be considered when available. Here it is important to consider the mechanisms that govern pile behaviour in static and dynamic loading, and actual deformations given the fact the set values should not exceed 12 mm during dynamic testing (Paikowsky, 2001) given the loss in reliability in the results of the signal matching analyses.

6 SENSITIVITY CHECK

ISO also recommends that "the sensitivity of the predicted pile compressive resistance to the selection of different parameters" be checked. ISO notes that "if the compressive resistance of the pile is sensitive to changes in the parameters, the upper and lower bound pile compressive resistance should be given." In the authors' experience, reporting a range of potential geotechnical resistance values as part of the results has not been adopted by the industry despite numerous studies such as Fellenius, 1988 and Verbeek, 2018 that suggest the lack of a unique solution. Based on the authors' experience, a relatively wide range of calculated resistances have been observed from signal matching of large diameter pipe piles in deltaic and alluvial soils on the west coast of British Columbia, Canada, as noted previously.

ISO further states that "if the signal matching can be shown to be insensitive to parameter variation then the best match solution can be considered for determination of the pile compressive resistance." The key point of this statement is "shown to be insensitive". Software suppliers typically provide some guidance with the training of the software users. Typically, a "sensitivity" or "robustness" check includes either doubling and halving the damping or yield stresses and then carrying out an automatch to determine if the software trends back to the original inputs or finds a new "best match" (i.e., a new low match quality number).

Finally, signal matching produces a resistance distribution along the pile shaft and a resistance at the toe. ISO notes that this distribution "should be compared to the information from a geotechnical investigation. The resistances predicted for the tip and shaft, and the ratio of the tip to shaft resistance, should be checked to see if they are in reasonable agreement with those that would be anticipated from local ground conditions and experience." Again, it is inferred that "experience" means experience with the method and pile type in the local area and also access to actual static loading test data for similar piles.

6 RATIO OF RAM WEIGHT TO TARGET RESISTANCE

ASTM D4945-17 and ISO recommend that the weight of the ram (W_r) should be in the range of 1% to 2% of the target static geotechnical resistance to be mobilized (R). AS2159 provides some additional guidance with respect to hammer energy indicating that "the dynamic pile test shall be carried out using hammer energy sufficient to mobilize the pile strength requirements" and "the ultimate geotechnical strength of the pile will only be measured if sufficient energy is delivered to the pile in a single blow to mobilize all of the available pile shaft and base resistance."

The authors note that, while the ratio of the weight of the ram to the required mobilized resistance can certainly fall outside of the suggested 1% to 2% range, caution is required when using significantly lower or higher ratios. In the geological conditions present in and around the Vancouver area in British Columbia, Canada, including the Fraser River Valley and Fraser Delta, the practical lower limit seems to be somewhere around a W_r/R ratio of 0.8% to 0.7% for large steel pipe piles with L/D ratios in the range of 20 to 60, where the hammer is the limiting factor. W_r/R values as low as 0.5% have been reported on occasion but, on closer scrutiny, independent review demonstrated that the ratio was probably closer to 0.7% or 0.8%. To put this in perspective, large diesel hammers such as the APE D220 or APE D320 with ram weights in the range of 216 kN and 314 kN, respectively, would typically be expected to mobilize maximum compressive resistances in the range of 29 MN and 42 MN, but certainly not in excess of 40 MN and 60 MN.

7 OTHER CONSIDERATIONS FOR DYNAMIC TESTING AND SIGNAL MATCHING

It is apparent that the standards do not favour (and should not favour) one particular hardware or software supplier over another. Provided that the equipment used to collect the data in the field functions in accordance with the standards, the signal matching software is capable of performing the required modelling of the pile and the soil, and that qualified users are performing the work, there is no valid reason to specify the use of a particular type of hardware or software. The decision regarding choice of equipment and software should be left to the discretion of the qualified testing agency. In the authors' experience, our engineers use commercial software such as Pile Dynamics Inc.'s CAPWAP and Allnamics' AllWave-DLT for "typical" projects and also use software such as IMPACT developed by Mark Randolph of University of Western Australia and PLAXIS for more complex projects.

To facilitate independent review, the specifier should request that the field data be provided in a digital format such as ASCII or Excel to allow the data to be plotted and input into any signal matching software that may be preferred by the specifier or the specifier's reviewer. It would make sense for industry to agree on a standard data format. If a particular signal matching software is not able to read non-encrypted data, it is the authors' opinion that the industry encourages the software suppliers to adapt their software to do so. At one time, it was possible for all software to read unencrypted data but the feature has apparently disappeared in recent years with one of the most popular signal matching programs.

We would also suggest that equipment manufacturers consider the inclusion of optical sensors to measure pile head displacement with time to provide an independent check on the displacement data derived from the accelerometers.

8 CONCLUSIONS

Of the international standards reviewed, only ISO addresses what actually constitutes signal matching and provides guidance on what should be considered when signal matching. Further, the Standard highlights the importance of checking the robustness of the solution and provides guidance on reporting a possible range of solutions where the results are found to be sensitive to the input parameters. Based on work by Rausche (1991), ISO actually recommends presenting upper and lower bound solutions when this situation occurs. Unfortunately, in the authors' experience, this is not part of the current practice.

For dynamic load testing, it would behoove both specifiers and testing agencies to consider practical limitations of the method in terms of the resistance that can be mobilized for a particular size of hammer.

To facilitate independent review, industry should encourage hardware and software suppliers to adapt their software to read ASCII files or similar. The format of these files could be standardized to facilitate the exchange and interchange of information.

Finally, we suggest that matching of displacement should become standard practice and that equipment suppliers be encouraged to include a means of independently measure pile head displacement with time.

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