Worldwide dynamic foundation testing codes and standards

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ABSTRACT: Ten years ago, a paper by Beim, J. et al (1998) compiled worldwide codes and standards pertaining to high and low strain dynamic testing. That work predicted the development and implementation of many new, normative documents in the years to follow. The present paper intends to verify the extent to which that prediction materialized. It updates the 1998 list of codes and standards to reflect their most current reviews, releases or editions and summarizes the authors' process of identifying new codes and standards released throughout the world in the past 10 years. It also expands the 1998 code and standard review effort beyond high and low strain dynamic pile testing and into cross hole sonic logging and energy measurements on dynamic penetrometers for Standard Penetration Tests. Lastly, the paper discusses the implications of adoption of these codes and standards on foundation design and construction. For high strain dynamic tests, the paper reviews the differing philosophies of worldwide codes as applied to the effect of the employed foundation testing method and its reliability on the applicable factors of safety. Many codes have been adopting Load and Resistance Factor Design (LRFD) methods; these are briefly discussed. The overarching goal of this Codes and Standards review is to serve as a resource for foundation testers around the world.

1 INTRODUCTION

This paper presents a representative overview of the state of dynamic foundation testing codification and normalization throughout the world. When compared to other construction procedures, dynamic foundation testing is a relatively new concept. Having seen most of its development take place in the late 1960s and early 1970s, it did not see worldwide standardization and codification efforts take place until the late 1980s and 1990s. By 1998 codes and standards had proliferated sufficiently to warrant a compilation by Beim, J. et al. (1998). Other reviews (Goble, 2000; Likins 2004) focused mostly on high strain dynamic testing of foundations. This paper intends to update and expand on the 1998 effort, focusing not only on high strain testing but also on crosshole sonic logging (CSL), pulse echo testing and energy measurements on dynamic penetrometers.

Codes, Standards and Specifications are developed and enforced in manners that vary with the countries where they originate. We start by discussing some of these differences and commenting on terminology. Section 2 updates and expands the international compilation provided by Beim, J. et al. (1998). In 2.2, the authors focus in particular on the USA, their country of practice, while 2.3 presents results of a worldwide survey conducted by the authors. The implications of current foundation testing standards in design and construction are discussed in Section 3. Section 3.1 focuses on high strain dynamic load testing standards, and discusses safety factors. Section 4 concludes this work.

1.1 Private sector versus government standard and code development and enforcement

In many countries, the National Government oversees the regulatory development of codes, standards and specifications, as well as compliance enforcement (Chabot, C. L., 2007). This commonly results in a single national code. By contrast, in the United States the development of building codes and standards is a mostly private sector effort, with non governmental organizations playing a key role in voluntary standards development.

The US Government established the National Bureau of Standards in 1901; however USA manufacturers and the engineering community of the early 20th century resisted the creation of a Bureau of Standards modeled after its European counterparts. The American Society for Testing and Materials (now ASTM International) had been founded a few years before – in 1898 – in Philadelphia. During that period the American Society of Civil Engineers and other professional organization were also developing standard specifications for various industries. The by-laws of ASTM proclaimed its dedication to the development and unification of standard methods of testing (ASTM, 1998).

Private sector codes and standards developed in the US thus consist of procedural recommendations that aim to reflect state of the art and consensus industry practice, but, unlike many national codes, are not enforceable until legislation to adopt them is passed by State or Local government. One exception to the private sector code development effort is the Standard Specification for Highway Bridges, developed by the American Association of State Highway Officials (AASHTO), which is a government entity.

1.2 Nomenclature and usage

Beim, J. et al. (1998) note that in most cases specifications and standards describe testing procedures, while codes tend to describe a design and construction practice. Specifications and standards often become part of more encompassing construction codes such as the US-based International Building Code (IBC, 2006). While we attempt to be consistent with the nomenclature used in that original paper we heed the authors' advice that sometimes these documents are indistinguishable from each other, and acknowledge that some misnomers may occur in our work. Furthermore, the authors include manuals of practice issued by industry organizations when discussing the USA.

Dynamic foundation testing often refers solely to high and low strain dynamic testing; in the present paper, however, we include codes and standards relating to CSL and energy measurements on SPT tests. Low strain dynamic testing is sometimes referred to as pulse echo testing in the industry and in this paper.

2 COMPILATION OF CODES AND STANDARDS

2.1 United States of America

In the United States, codes, standards and specifications that normalize, accept or recommend nondestructive testing were already in existence in 1998. Ten years later, many existing standards have seen updates and revisions and new publications have emerged, some of them pertaining to crosshole sonic logging. These documents have also become more widely referenced by both the public and private sectors. We discuss some of the most relevant ones in the following paragraphs.

ASTM standards are widely recognized and referenced around the world as minimum requirements and correct testing procedures. ASTM D-4945-00 (ASTM, 2000) standardizes procedures for performing high strain dynamic testing. It was originally adopted in 1986 and is, at the time of writing of this paper, in the process of being revised. The standard for low strain integrity testing, ASTM D-5882-07 (ASTM, 2007), was adopted originally in 1995 and was revised in 2007 without major changes. ASTM recommends normalization of results from Standard Penetration Tests (ASTM, 1999) and requires it when SPT results are used to determine the liquefaction potential of sands (ASTM, 2004). D-4633-05 (ASTM, 2005), originally adopted in 1986 and substantially revised in 2005, states that the only accepted means of determining energy for normalization of N-values is by force and velocity measurements. ASTM did not have a standard for CSL in 1998. ASTM D-6760-02, at the time of writing of this paper under revision without major changes being proposed, standardizes the CSL procedure and was adopted originally in 2002 (ASTM, 2002).

The American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) jointly produce design codes and guideline specifications for foundation installation on transportation projects. State Highway Departments (also known as Departments of Transportation or DOTs) then adopt AASHTO specifications, reference it, or modify the guideline document. The Standard Specifications for Highway Bridges (AASHTO 2003) which was in place in 1998 and included a section on dynamic testing, has been superseded by the AASHTO Load and Resistance Factor Design Bridge (LRFD) Design Specifications (AASHTO 2007). This newer document, as did the superseded one, allows load testing by either dynamic or static methods. The document T-298-99 (AASHTO, 1999), originally published in 1993, standardizes the methodology for performing dynamic foundation testing on driven piles, drilled shafts, micropiles and continuous flight auger cast piles. Most State DOTs (e.g. Kentucky, New Hampshire, Ohio, West Virginia and others) have provisions modeled after AASHTO for allowing high strain dynamic testing methods to confirm foundation quality. AASHTO's draft proposed construction specifications for drilled shafts is expected to specify that CSL be used as a regular inspection method, while making reference to other non destructive test methods such as pulse echo testing as well. Some State DOTs (for example West Virginia DOT, 2003) already specify the execution of crosshole sonic logging in drilled shafts; others will likely follow suit.

Several building codes existed in the US up to 1999. These are gradually being phased out, as the three main regional building codes joined together in 2000 to produce a national one (IBC, 2006) which treats static load testing and dynamic pile testing as essentially equivalent. It is an Allowable Stress Design (ASD) code and assigns a global safety factor of 2.0 to either test. Similarly to the process of adoption of AASHTO documents by States Departments of Transportation, the International Building Code is

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adopted with or without modifications by States, Counties or Cities.

A manual used by the USA Army Corp of Engineers as the basis for planning, design and construction of pile foundations for civil works structures (USACOE, 1993) was made available to the industry through its publication by the American Society of Civil Engineers. It guides geotechnical and structural engineers to incorporate high strain dynamic testing in the control of pile driving operations and in geotechnical as built analysis.

The Deep Foundations Institute issues manuals of practice for the deep foundations industry. While in 1998 it already recognized the practice of dynamic testing in construction (DFI, 1997) it has since published the Manual for Non Destructive Testing and Evaluation of Drilled Shafts (DFI, 2004) that recommends procedures for CSL, low strain pulse echo integrity testing, and high strain dynamic testing.

The American Society of Civil Engineers Standard Guidelines for the Design and Installation of Pile Foundation'' (ASCE, 1996) refers to dynamic testing as routine practice and takes the approach of multiplying partial safety factors to obtain the overall factor of safety. This document is currently undergoing a revision process and the draft document includes both crosshole sonic logging and low strain integrity testing as viable options for assessing foundation quality. It is also expected to include both ASD and Load and Resistance Factor Design (LRFD) provisions, allowing a leaner design when more testing is performed (Likins, 2004).

The Installation Specifications for Driven Piles (PDCA, 2007) includes dynamic foundation testing methods in quality control. Recommended Design Specification for Driven Bearing Piles (PDCA, 2001) contains two design procedures – ASD and LRFD – and allows the performance of high strain dynamic tests. This document also reduces the safety factor, or increases the resistance factor, when the amount of testing increases with the reasoning that more tests reduce uncertainties. These industry consensus documents are produced in a form suitable for adoption by reference in general building codes.

2.2 Other countries

Information Codes, Standards and Specifications of countries other than the USA were obtained primarily by sending a survey (APPENDIX) to 472 individuals who perform one or more forms of dynamic foundation testing. The authors consider these individuals sufficiently knowledgeable about the state of the industry in their country of practice for their responses to be deemed accurate. Forty nine practitioners from 28 different countries answered the survey.

In 1998 six countries other than the United States were identified as having a National Code and/or a widely accepted Industry Standard pertaining to High Strain Dynamic Load Testing – Australia, Brazil, Canada, China, Germany (at that point in draft format), and the United Kingdom. Four of those (Australia, China, Germany and the United Kingdom) had a National Code and/or an Industry Standard pertaining to Low Strain Dynamic Testing as well. France had a Low Strain but not a High Strain Dynamic Testing code. China, France and the UK had documents normalizing or recommending the use of CSL for quality control of drilled shafts (Beim J, et al, 1998). In the past 10 years many of these documents have been or are in the process of being updated. We refer the reader to the 1998 paper for the relevant aspects of these codes; the following paragraphs mostly discuss changes, updates or modifications.

An updated version of the Australian National code (SAA, 1995) is slated for publication in 2008 and will give more emphasis to foundation testing, including, in addition to the current sections on high and low strain dynamic load tests, provisions for cross hole sonic logging and rapid load testing (Chambers, 2007).

Brazil has updated its high strain dynamic load testing standard in 2007 to include additional details on test execution, instrument calibration and to require one CAPWAP® analysis (the software is mentioned by name on the standard) per pile tested (ABNT, 2007).

In 1998, the only Canadian province that included dynamic load testing in its code was Ontario. While CAN/CSA-S6-06, the Ontario bridge code (CSA, 2006), is still enforced only in Ontario, it is now adopted by policy in other provinces and municipalities (Gillespie, 2007). In addition, the British Columbia Ministry of Transportation issued a supplement to the Ontario document (British Columbia Ministry of Transportation, 2007) that includes additional comments regarding high strain dynamic load testing and force and velocity measurements for the determination of SPT hammer energy. The supplement is required in British Columbia for bridge design and supersedes CAN/CSA-S6-06. In Canada, structures other than bridges have to comply with the National Building Code of Canada (NRCC, 2005). This enforceable code is similar to the other two codes in the resistance factor it specifies for dynamic tests.

China, a country that by 1998 had several provincial specifications and a code allowing high strain dynamic load testing of foundations, now exhibits a myriad of documents covering not only high but also low strain dynamic load testing and CSL. These documents are published by various ministries (enforceable codes at the national level), provinces, municipalities and non-governmental industry organizations. Of the test methods the authors have researched, only SPT energy measurements are not normalized. Table 1 summarizes the information.

European countries cited by Beim J. (1998) have, as other nations, updated their specifications and codes.

Table 1. Specifications, codes and standards in China (Liu, 2007)

Name	Serial No.	Scope of standard
Specifications for foundation piles for port engineering	(JTJ254-98)	Design and construction
Specifications for pre tensioned large diameter concrete pipe piles for port engineering	(JTJ 261-97)	Design and construction
Specifications for Pile dynamic testing for port engineering	(JTJ249-2001)	Pile dynamic testing
Technical specifications for concrete defect examination with super sonic wave	(ECS21.90)	CSL
Pile static load testing specifications for port engineering	JTJ255-2002	Static pile test
Code of pile bearing capacity testing using self balancing method	DB32/T291-1999	Pile testing with self balancing method
Technical specifications for pile foundation of building	JGJ94-94	Design and construction
Technical specifications for pile foundation examination of building	JGJ106-2003	Dynamic pile testing, static pile testing
Technical specifications for non destructive concrete testing for port engineering	JTJ/T272-99	Dynamic pile testing and CSL
Design standard for foundation of buildings	(GB50007-2002)	Design

We briefly review their present situation, noting that Eurocode (discussed in more detail later in this paper) is in the process of changing the landscape of codification in the region.

In France, low strain testing (AFNOR, 1993) and crosshole sonic logging (AFNOR, 2000) norms were in place in 1998 and have been updated; the codification of high strain dynamic load tests has since emerged but is still an experimental norm (AFNOR, 1997).

In 1998, several German DIN codes pertaining to foundations existed and were enforced, however procedures for performing dynamic tests (based on recommendations from the German Society of Geotechnics) have evolved in the past decade from draft to final recommendations for both low and high strain dynamic testing (DGGT, 2007).

As is the case in the United States, no government code exists in the United Kingdom. The industry however, has for long followed the specifications of the Institution of Civil Engineers for low and high strain dynamic tests. That document is now on its second edition (ICE, 2007).

In Sweden, work is being done to reconcile the recommendations of the Commission on Pile Research and of the Swedish Geotechnical Institute and the latest edition of national code for highway bridges (SNRA, 2004) with the European Standards that will be used in a year or two (Grävare, 2007).

Our survey has also identified a handful of countries where codification of foundation testing either had not been identified by Beim J. (1998), or has emerged in the past 10 years.

National codes for low strain integrity testing (VMC, 2005a) and for cross hole sonic logging (VMC, 2005b), which are based on ASTM standards, now exist in Vietnam. No codes mention high strain dynamic testing.

In Argentina, in spite of the absence of national codes or specifications, high strain dynamic load tests are now sometimes required by provincial governments. Low strain tests, while not accepted for bridge foundations, are often required by private owners. Cross hole sonic logging has recently started to be required for bridge foundations by certain provincial transportation officials (Prato, 2007).

The Egyptian Code for Soil Mechanics and Foundations, first issued in 1991, reflects the use and acceptance of the Low-Strain, High-Strain Dynamic Testing of piles and its associated analyses. The latest version (RCHBPP, 2006) of the code describes and accepts the use the integrity testing of piles by means of Cross-hole Sonic Logging.

Although Mexico does not have a national code pertaining to foundation testing, the Mexico City Code (Mexico DF, 2004) is now based on LRFD design and refers to high strain testing as an alternative method.

A similar situation exists in the Philippines – specifications for foundation testing are dependent on the location and nature of the project. For buildings more than 4 storeys high and in larger cities like Manila, and for government projects, integrity tests (low strain or CSL) and load tests (dynamic or static) are required (Reyes, 2007).

The Public Works Department of the Malaysian government is currently sponsoring the development of guidelines and specifications for high strain dynamic pile testing (JKR, 2005).

The Ministry of Surface Transport Specification from the Indian Roads Congress (MOST 1988), currently under revision, briefly mentions dynamic pile testing. India also has a basic document governing pulse echo testing (BIS, 2001) which is due to be revised at a yet unspecified future date. There are no codes or guidelines for CSL in India (Vaidya, 2007).

The Qatar Construction Specifications (QCS, 2002) allows "alternative methods for testing piles", including pulse echo testing and sonic logging for integrity, and dynamic load testing for capacity determination.

Denmark's Code of Practice for foundation engineering (DGI, 1998) allows the performance of dynamic load tests as a possibility (although with the same partial safety factor as the "Danish Driving formula") but does not mention pulse echo testing or cross hole sonic logging tests. As of January 2008 the Eurocode with the approved Danish Annex will be in force in Denmark.

Similarly, the Polish Code offers some guidance on high strain testing, but not on integrity testing methods (PCSN, 1983). It is currently being used in conjunction with the Pre-Norms of Eurocode (Maciocha, 2007).

The emergence of Eurocode is one of the most significant development in codification in the past 10 years – and one that will no doubt affect a large number of countries. Structural Eurocodes – commonly referred to as Eurocodes – are a set of ten European Standards that contain common structural rules for the design of buildings and civil engineering structures. Eurocodes are managed by CEN (Comité Européen de Normalisation) which is comprised by the national standards bodies of all European Union countries plus Iceland, Norway, Switzerland and Liechtenstein (CEN, 2007). Volume 7 of the Eurocode pertains to geotechnical design (CEN, 1997).

Each European country is currently developing National Annexes which translate and complement Eurocode. These Annexes will then be adopted and enforced by each nation. National Annexes will include Nationally Determined Parameters specific to individual member states. These national parameters will allow the EU member states to choose the level of safety applicable to works in their territory, will contain country-specific data, and, when alternative methods are allowed in the Eurocode, will state the method to be used by the country. National Annexes should not, however, alter any provisions of Eurocode (CEN, 2003).

Eurocode is a progressive LRFD code (Likins 2004) that allows high strain dynamic testing, specifies a minimum number of load tests per job site, and allows the use a lower safety factor when more tests (static or dynamic) are conducted.

Eurocode also allows low strain dynamic testing for integrity verification but is not definitive in its reference to CSL (Klingmüller, 2007).

For Standard Penetration Tests, a European Standard developed jointly by European Committee for Standardization and the International Standards Organization specifies that the driving energy per impact be checked every six months. The recommended method to determine the actual energy is by force and velocity measurements (CEN, 2005).

Responses to our survey that originated in European countries lead the authors to believe that National Annexes will follow Eurocode 7 in its recommendations pertaining to dynamic foundation testing.

3 DISCUSSION OF CURRENT STANDARDS

This section discusses how the philosophy of a representative subset of the codes discussed in the section 2 influences design and construction practices. We discuss each of the major types of dynamic testing in this work separately.

3.1 High strain dynamic testing codes and standards

Many countries, including the USA, have been observing a tendency towards LRFD-based codes and standards. These codes require that foundations be designed for a required "nominal resistance" (also known as "characteristic or ultimate capacity") which, reduced by a resistance or partial safety factor, has to exceed a factored load. LRFD recognizes that different loading conditions have different uncertainties and therefore assigns different load factors to different load conditions (Likins, 2004). Similarly, resistance factors vary with the capacity verification method and sometimes with the numbers of load tests performed. Depending on the code and country, resistance factors may multiply the nominal resistance and be less than unity and, or divide into the nominal resistance and be greater than unity, but in either case the net result is essentially the same and the factored resistance is higher for more accurate resistance determination methods and lower for less accurate methods.

The US-based AASHTO LRFD code (AASHTO, 2007) intends to calibrate load and resistance factors from actual bridge statistics (FHWA, 2007). Fortunately foundation failures are low probability (albeit high consequence) events, thus limiting data availability for a statistical analysis. Resistance factors specified in the AASHTO code sometimes result in factors of safety that are significantly different from current US practice (Rausche et al, 2007).

Some of the codes reviewed in this paper treat static load tests and dynamic load tests as equivalent, and thus recommend the use of the same safety factors for either test. Examples are the Brazilian code (ABNT, 2007), German recommendations (DGGT, 2007), the specifications currently being developed in Malaysia (JKR, 2005) and the IBC code (IBC 2006). This is justified by considering that dynamic testing is generally statistically conservative, for driven piles is often performed at end of drive (before additional set-up results in higher capacities), and is usually performed in significantly higher numbers than static tests, allowing better coverage of the site and thus lowering the risk of failure.

In codes from other countries (Australia, Canada, and European countries), dynamic tests require the use of higher safety factors – or more severe capacity reduction factors – than static load tests (the difference is typically 10%). This is usually justified by considering static load tests as the standard and assuming that the 10% difference helps cover the statistical variation between tests. It should be noted, however, that various approaches to the interpretation of static tests can lead to differences in assumed failure loads of factors as high as 2 (Duzceer and Saglamer 2002).

Documents such as the Australian code (SAA, 1995), Eurocode 7 (CEN, 1997), German (DGGT, 2007) and Swedish (SNRA, 2004) industry recommendations, ASCE (1996) and PDCA (2001) allow lower safety factors (or less severe capacity reduction factors) depending on the amount of load testing performed. The more testing, and the more accurate the testing method, the lower the global safety factor for design. While additional testing increases the overall reliability of the foundation, the use of a lower safety factor results in a less conservative design. The reduction in total construction costs is usually significant, offsetting the costs of additional testing (see Appendix B for an example). While in some countries there is no specification determining how much testing is to be performed, codes or recommendations of others – Brazil, Canada, China and Germany among them – recommend a certain percentage of piles to be tested. Rather than a percentage, Eurocode 7 recommends a certain number of piles to be tested. The fixed number recommendation leads to percentages of tested piles that are naturally much higher in small projects than in large ones.

3.2 *Low strain dynamic testing and crosshole sonic logging codes and standards*

The past decade has seen an ever growing awareness of the need to verify the structural integrity of foundation elements, particularly drilled and cast in place foundations, which cannot be visually inspected prior to concreting and that are installed by an ever increasing variety of equipment and construction methods. This has translated into an increased number of documents that recommend or specify pulse echo or CSL procedures.

France should be noted for including both time domain and frequency domain analysis among its standard procedures (AFNOR, 1994).

To the extent that our research could determine, the only normative document for performing CSL before 2002 was the French norm (AFNOR, 2000). The adoption of D6760 (ASTM, 2002) has given the foundations industry another standard for performing this test, and one that has been referred to by several respondents of our survey as the de facto standard in their countries.

3.3 *SPT energy measurements codes and standards*

The only significant documents identified by our research that specify force and velocity measurements for energy calibration of SPT tests are ASTM standards (ASTM 1999, 2004 and 2005) and the European Standard jointly developed with ISO (CEN, 2005). In the US, however, a number of State Highway Departments (Ohio, Minnesota, and others) require in their construction specifications the periodic calibration of the SPT equipment.

4 CONCLUSIONS AND FUTURE OUTLOOK

While we have attempted to research multiple countries and present a comprehensive review, the results presented herein are by no means exhaustive, and omissions of nations where pertinent documents exist may easily have occurred. We trust, however, to have provided a useful resource for practitioners and for individuals interested in contributing to the development of standard documents in their countries.

In general, responses to our survey have revealed several codes that permit or encourage the practice of dynamic foundation testing and the widespread use of standards for properly conducting the tests.

Where national standards or specifications are lacking for one or more dynamic testing method, the industry in the vast majority of countries surveyed (e.g. Brazil, Egypt, Honk Kong, Indonesia, Kuwait, Mexico, Philippines, Qatar, Saudi Arabia, Thailand, Vietnam) adopt ASTM standards as the minimum requirements for proper test execution.

Looking into the future, of significant importance are the trend towards LRFD based codes and the acceptance of dynamic testing by the unified European code. The latter could gives impetus to more widespread practice of dynamic testing in various countries in Europe.

The authors foresee a continuation of the trend towards codes that allow lower safety factors (or higher resistance factors) when more testing is conducted, thus giving the industry an opportunity to realize the advantages of enhanced dynamic testing programs.

Where force and velocity measurements for energy calibrations of SPT tests are concerned it is expected that the adoption of EN ISO 224760-2 (CEN 2005) by European countries will increase reliance on these measurements for calibration of SPT tests.

On the integrity testing front, the number of codes and specifications pertaining to crosshole sonic logging is still relatively small. The authors attribute this – at least in part – to the still relatively recent adoption of the ASTM document that normalizes CSL procedures (ASTM, 2002). In contrast, the ASTM code that standardizes high strain dynamic testing was first adopted in 1986. The authors believe that, in the coming decades, crosshole sonic logging specifications and codes will rapidly become more common around the world.

We are encouraged by the fact that the survey of dynamic foundation testing codes and standards has confirmed the prediction (Beim, J. et al, 1998) of emergence of many new, normative documents in this field. We expect this positive trend to continue in the years to come.

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APPENDIX A

1) Is there a National Code in your country that pertains to or has a chapter relevant to Foundations?
2) If you answered yes to question 1, is the code enforced by the government?
3) If there is no National enforceable code, are there non-governmental industry standards, specifications, guidelines or recommendations followed by the foundations industry?
4) If you are in Europe, do you need to comply with Eurocode?
5) In your country, which codes, standards, specifications, guidelines or recommendations, if any, deal with (please list complete name of code, with year of last revision. List as many as applicable):
    1. high strain dynamic foundation testing (PDA)
    2. low strain dynamic foundation testing (PIT, pulse echo testing)
    3. cross hole sonic logging (CSL)
    4. energy measurements of SPT hammers
6) If your country does not have a code, standard or specification dealing specifically with foundation

testing procedures, do you use a US-based or UK-based standard, or a standard from another country (please specify the country or code used), instead?

7) Do you have comments on the subject of codes and standards that you would like to contribute?

APPENDIX B

A global factor of safety in LRFD is the combination of reduced resistance (relative to the nominal or characteristic resistance determined in a load test) and increased loads. Lower global safety factors are not just an abstract idea, but have serious cost savings consequences, as shown in the example based on the USA-based PDCA design code (PDCA, 2001). That code specifies a safety factor for each different method of capacity assessment.

Consider a 2000 ton column load and a 200 ton ultimate pile capacity per pile. For each capacity evaluation method a pile design load is computed by dividing 200 tons by the corresponding factor of safety. The required number of piles is the total column load divided by the pile design load, as shown in Table 2.

Table 2: Foundation design based on PDCA specification

Method	Factor of Safety	Design Load (tons)	Number of piles required
Dynamic formula	3.5	57	35
Wave Equation	2.5	80	25
2% dynamic testing	2.1	95	21
10% dynamic testing	1.9	105	19
0.5% static testing	2.0	100	20
2% static testing	1.8	111	18
15% dynamic test plus one static test	1.65	121	17

Percentages are number of tested piles per total piles on site.

In this example, a higher percentage of tested piles and the use of a more reliable capacity evaluation method result in fewer piles. Reductions of up to 50% in the required number of piles per column are shown. In a large structure with multiple columns reductions of this magnitude could yield significant savings in total foundation costs. In codes that adopt a similar philosophy (Eurocode 7, Australia) adding extra tests not only results in safer foundation but, for larger projects in particular, also in the lowest cost foundation as well.

Stress Wave

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Application of Stress Wave Theory to Piles

Science, Technology and Practice

J.A. Santos
Editor

For Performing dynamic, testing the software should be compiled and executed and parameters such as memory usage, CPU usage, response time and overall performance of the software are analyzed. Dynamic testing involves testing the software for the input values and output values are analyzed. Dynamic testing is the Validation part of Verification and Validation. Dynamic Testing Techniques. The Dynamic Testing Techniques are broadly classified into two categories. They are Fugro's geotechnical and foundation engineering team delivers specialised deep foundation testing services. Increasingly heavy and complex projects require solid site data. Fugro's extensive suite of load-testing tools ensures the long-term performance of foundations.Â We provide state-of-the-art and traditional deep foundation testing services with a focus on enabling foundation design optimisation and assurance of long-term performance together with assurance of deep foundation suitability in even the most complex site conditions and loading scenarios. Some parts of the SuiteCRM code structure for PHP markup are inconsistent in their style. SuiteCRM are working to gradually improve this by helping our internal team and contributors maintain a consistent style so the code can become clean and easy to read at a glance. This will be an ongoing transition but we encourage users to begin to think about their supplied bug fixes and enhancements to conform to the below standards. We thank you for your continued contributions! License. At the beginning of each new core file include the following license as the standard header.Â The interactive user interfaces in modified source and object code versions * of this program must display Appropriate Legal Notices, as required under * Section 5 of the GNU Affero General Public License version 3. * *