A BRIEF HISTORY OF THE APPLICATION OF STRESS-WAVE THEORY TO PILES

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ABSTRACT: A summary of the early scientific research that forms the basis of the development of one-dimensional wave mechanics is first summarized. Beginning with the work of Donnell in the early 20th Century the subsequent analytical and computational research is reviewed in some detail. The early "wave equation" computer programs beginning in the 1940's are described and discussed including the applications that motivated the entire development up to the present. Early measurement techniques are reviewed briefly up to the development of the resistance strain gage. This device made possible routine measurements of the force wave in the pile. The development of an accurate and reliable accelerometer was somewhat slower than the force measurement capability but usable devices were available by the time of the Michigan pile tests of 1960. The modern era of pile measurements and analysis began in earnest with the research at Case Western Reserve University. The methods for dynamic pile capacity predictions are summarized up to the present. It is estimated that today over 5000 job sites are tested and analyzed annually. The history of low strain integrity testing is presented briefly and the history of the International Stress Wave Conferences is summarized. Finally a list of American codes and standards relating to this topic is included.

INTRODUCTION

The use of piles in construction work dates back many centuries. Herodotus, the Fourth Century B.C. Greek writer and traveler, also known as "the father of history", provided the first documented historical reference to piles. Ancient Egyptians, Greeks, Phoenicians, Romans, Chinese, Mesopotamians, and others all used piles. In Lake Constance, located between Switzerland and Germany, archeologists found well preserved remains of wood piles, which are estimated to be 2000 to 4000 years old.

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These piles supported the houses of lake dwellers who built them in the lake for safety from attack. Pons Sublicius (bridge of piles) is one of the oldest Roman bridges; and the construction of the pile supported bridge across the Rhine River by Julius Caesar's army is well documented. More than 1300 years ago, the city of Venice was established and built on piles in the marsh delta of the Po River; Amsterdam, established over 1000 years ago, was founded almost entirely on driven piles.

Piles continue to be used today as deep foundations to support many types of structures in varied geotechnical/geologic conditions on land and at sea. Due to their essential role in supporting structures, the substantial effort and cost involved in their construction, and the potentially disastrous consequence of their failure, there has always been a desire and need to evaluate piles according to contemporary state-of-the-art knowledge.

Rudimentary application of dynamic analysis of pile driving originated with the adoption of Newton's theory of rigid-body impacts. Due to its simplicity of application, this approach became popular with practitioners and the resulting so-called "dynamic formula" conveniently produced approximate results. According to Terzaghi (1943), Newton himself warned against the application of his theory to impacts such as produced by pile driving hammers. In current practice, such dynamic formulas are losing favor. However, they may still be of limited utility if site calibrated on small jobs where the cost of a more refined method of evaluation cannot be justified.

More recently, it has been recognized that the dynamics of pile driving is more accurately represented by stress-wave propagation theories and analyzed based on principles of one-dimensional wave mechanics in elastic rods. Hindered by the complexity of the mathematical formulations and the difficulty of realistically representing the system components in a sufficiently accurate manner, early closed form stress-wave analytical methods had no practical solutions for the analysis of pile driving until about the middle of the 20th Century. Only relatively recently, i.e., within the last 25 years, has the availability of the digital computer and electronic measuring devices made it possible for the practical, economic, and routine application of the stress-wave theory to piles.

EARLY DEVELOPMENTS

The study of dynamics of bodies in motion had its beginnings in Galileo's (1564-1642) famous experiments on falling bodies, and his treatise "De Motu Gravium" prepared in 1590. In 1678, Robert Hooke (1635-1703) published the first scientific treatise, "De Potentiâ Restitutiva," discussing the elastic properties of materials. In it, *Hooke's Law* was introduced relating force and deformation and this development became the foundation of the mechanics of elastic bodies. The French army engineer Charles Augustin Coulomb (1736-1806) contributed greatly to the study and understanding of the mechanics of elastic bodies. Of special note is his paper "Sur une Application des Rugles de Maximis et Minimis à Quelques Problèmes de Statique Relatifs à L'architecture" presented in 1773 to the French Academy of Sciences and published in *Mém. Acad. Sci. Savants Ȅtrangers* in 1776. Perhaps best known in geotechnical engineering for his pioneering work on earth pressure theories, Coulomb also produced fundamental contributions in the fields of electricity and magnetism. Further progress was made by Navier (1785-1836); in 1820 he presented a memoir to the Academy of Sciences including the fundamental equations of the mathematical theory of elasticity.

Thomas Young (1773-1829) published his 2-volume work "A Course of Lectures on Natural Philosophy and the Mechanical Arts" in London in 1807. Among his contributions (e.g., introducing the notion of *Elastic Modulus*) was his pioneering method to compute stresses in elastic bars brought about by longitudinal impact considering stress-wave propagation. Eaton Hodgkinson (1789-1861) contributed by practical experimental work on the effects of axial impacts on beams. His results were published in the *British Association Reports* for the years 1833-1835.

Barré de Saint-Venant (1797-1886) was a brilliant scientist, outstanding engineer, and courageous man. He was first in his class at the École Polytechnique, was exceptionally admitted to the École des Ponts et Chaussées without examination. At the age of 17, as a school detachment first sergeant in 1814 when the allied armies were approaching Paris, he stepped from the ranks proclaiming: "My conscience forbids me to fight for a usurper ..." (Timoshenko, 1953). Saint-Venant produced inventive solutions (first by unsuccessfully utilizing trigonometric series, and later by closed form expression) to the problem of an elastic bar fixed at one end and struck axially at the other end. Joseph Valentin Boussinesq (1842-1929) was Saint-Venant's most distinguished pupil. Boussinesq solved the longitudinal impact of prismatical bars problem in terms of discontinuous functions. In 1883, Saint-Venant produced computational tables and diagrams illustrating longitudinal impacts for different weight ratios of the struck bar to that of a striking mass based on Boussinesq's solution (Timoshenko and Goodier, 1951). He showed that the maximum stress may occur at the fixed end of the bar.

Heinrich Rudolph Hertz (1857-1894) studied in Berlin under Gustave Robert Kirchhoff (1824-1887) and later made important advances, amongst them contributions to the theory of compression of elastic bodies where he presented solutions in numerical tables to simplify practical applications for engineering purposes.

The study of mechanical vibrations and harmonics originated from the ancient investigations of vibrating strings in musical instruments. Pythagoras (582-507 B.C.) conducted experiments which showed that for two like strings subjected to equal tension, if one is twice the length of the other they produce tones that are an octave apart. The early lyre makers had a working knowledge of the interrelationships between density, length, tension, and frequency. Joseph Sauveur (1653-1716) is generally credited with the first attempts to compute the frequency of a vibrating string, a task that was later accomplished by Brook Taylor (1685-1731) in 1713. John Wallis (1616-1703) is credited with observing the phenomenon of modes. Sauveur suggested the name "fundamental" mode for the lowest frequency of vibration, and "harmonics" for the other modes. Daniel Bernoulli (1700-1783) was the first to propose the principle of linear superposition of harmonies. J.B.J. Fourier (1768-1830) established the method of harmonic series which he presented in 1822 in his

"Analytical Theory of Heat Flow" (which illustrates the universality of general applicability of the method).

The equation derived for a vibrating string by Jean Le Rond d'Alembert (1717-1783) in 1747 is identical to that by Lagrange (1736-1813) for the organ pipe. This equation is now termed "**the wave equation**", even though the wave character of this type of vibration was not recognized at once (Burton, 1968). D'Alembert pioneered the study of partial differential equations and their application in physics and wrote most of the mathematical articles in the 28th Volume Encyclopédie. He submitted an article entitled: "Réflections sur la cause générale des vents" to the Prussian Academy for which he won the 1747 prize.

EARLY 20TH CENTURY ANALYTICAL ADVANCES

L. H. Donnell (1930) expanded St. Venant's relationships to those covering non-uniform bars and forces applied somewhere along the length of a slender rod. In a particularly insightful paper, D. V. Isaacs (1931), proposed that one-dimensional wave action be applied to the practical application of stress-wave theory to pile driving analysis. The following year, E. N. Fox (1932) published an important paper on stress phenomena occurring in piles during driving. The Proceedings of the First International Conference on Soil Mechanics and Foundation Engineering (that met on June 22-26, 1936, at Harvard University in Cambridge, Massachusetts, USA) contained a paper by A.A. Kanschin and A.A. Plutalow (1936) of the Technical University in Dnipropetrovsk, USSR in which they proposed a new formula for the determination of pile penetration under a hammer blow based on considerations of the progress of elastic waves by the impact.

In January 1940, the Journal of the Boston Society of Civil Engineers published a paper by A. E. Cummings (1940) in which he methodologically demonstrated the superiority of the stress-wave analysis method for solving longitudinal impact to pile driving over Newtonian-type impact energy formulas. Karl Terzaghi (1943) provides extensive discussions on the "phenomena of wave propagation [which] occurs in a pile after it has been struck by a falling hammer" and the application of "the theories of longitudinal impact on piles" for rational analysis.

In the late 1940s, while employed as Chief Mechanical Engineer by Raymond International, Inc., the premier American pile driving company at that time, Edward A. L. Smith produced the first general solution for the practical application of stress wave theory to piles. Smith was interested in finding a way to predict pile drivability (with emphasis on dynamic pile driving stresses) more effectively. He formulated a numerical solution using discrete elements with the finite difference equations. Although first solved by extensive hand computation, the method became practical by Smith's adaptation of the analysis to the newly developed digital computer. IBM programmed Smith's solution for use as a proprietary program by the Raymond Company and this work was apparently first discussed during an internal seminar at IBM in 1948. Smith's work is generally considered to be the first application of digital computers in a civilian engineering application (Schiffmann, 1995), and his landmark paper (Smith, 1960) is among the classics in the engineering literature.

Smith's model, methodology, and terminology (collectively termed the "Wave Equation") are still the basis for modern wave equation analysis.

During the 1960s, researchers at the Texas Transportation Institute (TTI) produced a public domain wave equation analysis computer program and performed important numerical studies related to the dynamic behavior of pile driving (Samson et al, 1963). Today the most widely used wave equation analysis program is WEAP, Wave Equation Analysis of Piles, first produced in 1976 by Goble and Rausche (1976) with sponsorship of the United States Federal Highway Administration (FHWA) and the New York Department of Transportation. WEAP contained the first public domain diesel hammer model that correctly modeled the thermodynamics of diesel combustion. The current program (GRLWEAP) has been continually improved both for ease of data entry, and to improve technical features such as pile residual stress analysis, pile-soil interface modeling, and drivability analysis. It must be emphasized the basic Smith model is still in use. Smith's work is one of the most remarkable technical achievements in civil engineering in the twentieth century.

Simultaneously with the wave equation work of Smith who pursued a discrete solution of the wave equation, K. J. de Juhasz (1942) developed a graphical method using the method of characteristics. H. C. Fischer of the University of Uppsala in Sweden further expanded on this process to solve a variety of practical pile driving problems. Thus, two approaches developed for the analysis of a pile under impact: the more flexible lumped mass method of Smith and the Donnell-de Juhasz method of characteristics. The latter method is more exact for ideally elastic, continuous systems. However, it is more difficult to apply to the pile capacity problem due to the difficulty of including a realistic soil, hammer and driving system model.

Starting in the 1950s, active worldwide construction of large fixed offshore platforms in deeper water for the petroleum industry coincided with, and perhaps inspired, developments in the application of stress-wave analytical methods for the analysis of pile driving. Driving long steel pipe piles to high capacities with conventional impact hammers presented special engineering and construction challenges that required these new analytical approaches and tools. Thus, the wave equation computer analysis programs were initially applied to evaluate the driveability of offshore piles. Today, dynamic pile testing is routinely performed as an integral part of offshore pile installations for assessments of hammer driving system performance, pile driving stresses and structural integrity, and soil resistance and pile load bearing capacity.

EARLY MEASUREMENTS

Experimental work in the pre-electronic era was restricted to acoustical studies of vibrations at audible frequencies. Among the early experimental investigators was Bertram Hopkinson, who in 1914 devised a simple apparatus (known as "Hopkinson's Bar") consisting of a cylindrical steel bar several feet in length and about one inch in diameter suspended in a horizontal position by threads. This suspended rod, which swung in a vertical plane when impacted at one end, allowed for the study of stress-time duration of traveling one-dimensional elastic waves. In 1948, R. M. Davies developed an electronic version of Hopkinson's Bar (by using the bar as the "earthed conductor of a parallel-plate condenser," together with an oscillograph, and a radio-frequency timing wave) for a detailed study of stress-wave propagation. Davies' experiments measured the shape and duration of the traveling stress-wave and confirmed predictions based on the earlier theories of elasticity.

In 1938, strains were measured in a concrete pile during driving using a novel strain measurement device developed by the researchers at the British Building Research Station. Several hammer blow events were recorded during this remarkable test (Glanville et al, 1938). H. Grasshoff, in 1944, performed model tests of dynamic penetration of model piles at the Institute for Soil Mechanics and Foundation Engineering in Germany using high-frequency slow-motion photographic methods to study dynamic soil resistance by double graphical differentiation of the space-time diagrams (i.e., displacement) obtained from the tests.

In 1856, Lord Kelvin discovered that the electrical resistance of some metals changed when a wire of that metal was strained axially. He used this fact with a Wheatstone bridge circuit to measure resistance change due to strain. An unbonded strain gage was developed but proved difficult to use. Bonded single wires were attached for specialized laboratory research on strain measurements. The bonded wire strain gage was invented independently by Edward E. Simmons at the California Institute of Technology (Caltech) in 1936 and Arthur C. Ruge at the Massachusetts Institute of Technology (MIT) in 1938. This device later became commercially available under the name "SR-4" gage and it made routine strain measurements possible.

With the development of the bonded resistance strain gage, dynamic pile measurements became much easier. L. Bendel from the University of Lausanne, Switzerland, reported on pile measurements made in the late 1940s using resistance strain gages and a dynamic strain recorder F. B. J. Barends (1992) mentioned, in the Preface to the 4th Stress-Wave Conference Proceedings measurements with resistance strain gages, by Sanders and Roe under the supervision of Van der Veen in 1952 in the Netherlands. In 1956, A. Verduin reported on stress-wave measurements during pile driving for Jetty 1 of the Rotterdam Harbor in the Netherlands. Also, E.A.L. Smith reported on the use of strain gages in a 1957 laboratory experiment to study dynamic tension waves in concrete piles. Yet, these early measurement attempts, in all cases, were terminated in a short time with no practical application or continuing program of research. The accomplishment of dynamic pile strain measurements was an end in itself.

A major advance in dynamic pile measurements occurred in 1960 when W. S. Housel (1965) directed an extensive study by the Michigan State Highway Commission, USA, to measure pile driving hammer performance. Measurements were made during driving of about 40 piles driven at three sites. The piles were also load tested. The primary purpose of the measurements was to evaluate hammer performance by measuring the energy transmitted to the pile. Force was measured at the pile top by a large force transducer and acceleration was measured on the force transducer. From these measurements, the transmitted energy was determined by integrating the product of the force and pile top velocity (obtained by integrating the measured acceleration). The measurement of acceleration has the advantage using the earth's gravitational field as a reference frame. This was the first case where acceleration was measured during pile driving and also the first time both force and motion measurements were made on piles.

Limited early acceleration measurements (with applications mainly in dynamometers, bridges, and aircraft) date to 1923 using a resistance-bridge-type accelerometer (called "Electric Telemeter"). Commercial development of accelerometers likely awaited the advent of the bonded resistance strain gage. Using the strain gage technology developed at MIT, J. Hans Meier constructed the first strain gage accelerometer (called "Elastic Dynamometer"). Per V. Bruel and Viggo Kjaer in Denmark developed piezoelectric accelerometers in 1943, and later introduced the first shear accelerometer in 1972. While accelerometer development occurred primarily in private industry, calibration capabilities evolved in government facilities. In the United States, the National Institute of Standards and Technology (NIST) has been involved in accelerometer calibration since the early 1950s. Patrick L. Walter has compiled the history of accelerometer developments (Walter, 1997).

THE MODERN ERA – THE CASE METHOD

The modern era of dynamic pile testing based on stress-wave measurements and analysis to evaluate hammer, pile, and soil performance utilizing routine field measurements and real-time data processing, started in the 1950s at Case Institute of Technology (now Case Western Reserve University) in Cleveland, Ohio, USA. Original scientific studies, innovative experimental work, and creative applied research at Case under G. G. Goble and with the contributions of Robert Scanlan and Fred Moses, produced a body of scholarly literature and state-of-the-art hardware measurement technology which made possible the practical application of stress-wave theory to high-strain pile analysis.

This research started with classified investigations on projectile penetration supported by the United States Department of Defense. When the Case Institute of Technology canceled all classified research in about 1955 the director of the project, H. R. Nara, supervised a small Case Institute of Technology research project to investigate the penetration of driven piles. A small model pile was driven into sand in the laboratory and measurements of pile top acceleration were made. Newton's Second Law was applied to the measurements at the instant of zero velocity and the pile was then statically tested. A volume of these tests was made and the dynamic prediction was compared with the static test results. A surprisingly good correlation was obtained (Eiber, 1958). A research project was funded beginning in 1964 by the Ohio Department of Transportation and the FHWA under the direction of Robert Scanlan and George Goble. After two years, Scanlan left Case and the research project. This project continued to receive financial support and sponsorships for research in the pile driving area until 1976 when Goble left Case Western Reserve University.

Routine dynamic pile testing at the Case project began on closed end steel pipe piles using foil strain gages that were mounted in the field and accelerometers that were bolted to the pile wall. The difficulty in mounting strain gages in the winter in northeastern Ohio and the time required, motivated the development of a force measuring system that used a specially designed top transducer. These relatively heavy top transducers (i.e., thick-wall pipes of similar pile diameter) were inserted between the hammer and the pile top. However, to accommodate different piles sizes, shapes (e.g., H-piles), and material types (e.g., concrete and timber piles), reusable "strain transducers" were developed which allowed rapid attachment by small bolts in any weather condition to any pile type or size. Due to their light weight and size they were more adaptable to remote job sites accessed by air transportation. Basically, this same system is the general method still used today, although the transducers have seen continued refinements. Both piezoelectric and piezoresistive accelerometers are now in routine use.

Early field measurements were recorded on light-sensitive, high-speed oscillograph paper and manually digitized and analyzed. A major improvement came in 1969 for recording data with the availability (at modest cost) of a portable, analog magnetic tape recorder that replaced the oscillograph. Large volumes of data could then be recorded, digitized and processed automatically.

The measurements of both force and acceleration at the pile top made possible the improvement of the analysis proposed by Nara and Eiber. By assuming the pile and total driving system as a single rigid body it was possible then apply Newton's Second Law at the instant of zero velocity. The method with correlations was originally presented by Goble et al (1967) and Goble and Rausche (1970), and later became known as the Phase I "Case Method" and this rigid body approach is now being used in other testing applications such as rapid load testing.

Improved analytical tools were simultaneously developed by the Case research team to assess the soil response, and hence pile capacity (Rausche, 1970 and Rausche et al, 1985). The original method was modified to represent the pile as an elastic rod. The resulting solution (Phase II) for bearing capacity took into account the stress wave effects on long elastic rods. This solution could be applied and solved in real time for each hammer blow by special purpose analog electronic equipment. Results were obtained, giving instantaneous answers for the capacity at the time of testing (during driving or later during restrike). By the mid 1970's with the advent of digital computation, improved analysis methods became available to improve the accuracy of the capacity prediction.

Using soil models similar to those developed for the wave equation analysis, the Case researchers also developed an analytical method called CAPWAP® (Case Pile Wave Analysis Program) in the late 1960's which replaced the hammer model of the wave equation with pile top measurements (Rausche, 1970 and Rausche et al, 1972). A set of soil resistances is assumed along the pile and at the toe. The program then typically inputs the motion (velocity integrated from the measured acceleration) and computes the associated force record. The computed force is compared with the measured force, and the soil model is adjusted until a good agreement between the measured and calculated force is obtained in a "signal matching" iterative procedure. The early program versions produced automatic solutions on main frame computers. However, the application to longer piles such as in the offshore oil work and the introduction of personal computers made user interactive solutions more attractive. With the increase in computational power available to modern personal computers and the spread of pile testing technology, automatic analysis routines for most land application piles has been refined and is now standard practice; the engineer may review and adjust the automated solutions.

Goble formed Pile Dynamics, Inc. and introduced the first commercially available "Pile Capacity Computer" (later renamed the "Pile Driving Analyzer®" (PDA)) in 1972, all through private funding. In an article entitled "150 Years of Geotechnical Design & Construction" (American Society of Civil Engineers' Geo-Institute's Geo-Strata magazine - October 2002), S. Trent Parkhill lists the introduction of the Pile Driving Analyzer by the Case project among the major developments in geotechnical engineering history. Initially, these PDA units used analog computation with digital readout of the final answers. In the 1982 version of the PDA, the increased speed of digital processors made it possible to perform the computations digitally.

While the initial goals were to evaluate pile capacity, it became apparent that pile driving stresses, pile integrity and hammer performance questions could be assessed by dynamic pile testing. Application to these additional uses led to increased benefit and increased use of the testing method. In fact, dynamic testing of offshore piles started in the 1970s primarily to assure adequate hammer performance, and readily became the norm for offshore pile acceptance. Dynamic pile testing continues to be routinely utilized worldwide for conventional offshore installations and in recent years, deep underwater construction. For land-based applications, dynamic pile testing is routinely applied as part of deep foundations works; it is estimated that dynamic pile testing is used on over 5000 job sites worldwide each year.

The earliest application of high-strain dynamic testing by stress-wave propagation methods for capacity evaluation of cast-in-place drilled shafts was in 1974 performed by George Goble and Garland Likins on a test shaft in Las Truchas, Mexico. Auger cast-in-place piles were first tested in the USA in 1977 by Frank Rausche and Garland Likins in Charleston, West Virginia, USA. Routine application to cast-in-place drilled shafts started in the early 1980s. The Proceedings of the Second International Conference on the Application of Stress-Wave Theory to Piles held in Stockholm in 1984 contains a paper (Rausche and Seidel, 1984) on the design, performance and correlation with static loading tests of dynamic tests on large rock-socketed drilled shafts as part of an extensive program for the West Gate Freeway in Melbourne, Australia. The same proceedings also contain a paper describing early dynamic testing of large bored piles in Germany (Seitz, 1984). Today, dynamic testing of cast-in-place shafts and auger-cast piles for capacity based on stress-wave methods is a well-established procedure in many parts of the world, particularly in Europe and Asia.

The application of high-strain dynamic testing has been recently expanded to also include instrumentation of Standard Penetration Tests (SPT) for the evaluation of hammer performance by measuring transferred energy to the top of the rod, and soil resistance characteristics for deep foundations design and analysis (Rausche et al, 1996). Another innovative application has been the recent use of dynamic pile testing technology on "Becker Drills" mostly in the Western United States for assessments of soil liquefaction potential in relation to earthquake studies.

LOW-STRAIN INTEGRITY TESTING

A discussion on the application of stress-wave theory to piles would not be complete without mention of low-strain integrity testing methods. In 1929, Solokov from the USSR was the first to suggest the quantitative use of ultrasonic waves for structural assessment of metal objects (Ultrasonic Testing, John Wiley & Sons publishers, 1982). Following significant developments in electronic instrumentation spurred by World War II, Firestone of the University of Michigan in the USA, and independently, Sproule of England, suggested the use of low-strain ultrasonic pulse-echo detectors to test for flaws in homogenous materials. Development of methods for testing concrete was slow due to the inherent difficulties in dealing with an inelastic, nonhomogeneous material that contains a large number of small voids (effectively "flaws"). J. R. Leslie and W. J. Chessman published an important paper on "Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures" in the Journal of the American Concrete Institute, September 1949.

Concrete does not transmit the type of high frequency waves that the early pulse-echo transducers were designed for. By the 1960s, there were commercially available systems for testing concrete structural elements utilizing low frequency stress waves generated by mechanical impacts and A. Dvorak in 1963 made an important contribution. Practical application for nondestructive integrity testing of deep foundations was developed in the 1970s first in Europe and later in the United States. In the 1960s, Jean Paquet of the Centre Experimental de Recherche et d'Etudes du Batiment et des Travaux Publics (CEBTP) in France did pioneering work on the application of low-strain stress-wave theory to pile integrity testing using a massive vibrator attached to the pile top and swept through a range of frequencies (Paquet, 1968), and in 1974 he applied for a patent on a method based on stress-wave analysis in the frequency domain. Paquet later applied the same frequency domain analysis to measurements of a hammer-induced impulse.

In 1966, defective caissons for the support of the John Hancock building in Chicago accentuated the need for integrity evaluation methods in the United States. Researchers at the Illinois Institute of Technology in the USA reported the results of extensive research including experimental laboratory work and field testing of full-scale production shafts using an accelerometer and oscilloscope with camera (Steinbach, 1971, Steinbach and Vey, 1975). These publications are excellent sources of early references on this topic.

Early pulse-echo tests were made with geophones and oscillographs in the time domain. Storage oscilloscopes greatly improved the application. Because of greater response characteristics, most pulse echo testing today uses accelerometers as the motion-sensing device, and mostly records are analyzed in the time domain. The hammer may also be instrumented when frequency domain analysis is desired. The proceedings of the first International Seminar on the Application of Stress-Wave Theory to Piles held in Stockholm, Sweden, in 1980 contains a technical paper by H. van Koten and P. Middendorp describing analog equipment and data interpretation methods for low-strain pile integrity testing (Van Koten and Middendorp, 1980). By the 1984 Stresswave conference, the low strain equipment reported by L. Schaap (1984) and J. de Vos et al (1984) was digital. With this major development of digital recording and processing of results, advanced data processing became possible and the range of application was greatly extended (Likins and Rausche, 2000). By the late 1980s, application of the low-strain pulse-echo method was expanded to cover evaluation of piles under existing structures for determination of unknown pile lengths (Hussein et al, 1992).

The CEBTP in France developed Cross-hole Sonic Logging in the late 1970's. This method requires tubes to be placed during initial shaft installation for probe access, a major limitation, but can be very effective in concrete quality evaluation and in assessing the extent and quadrant of defects. This method is digitally based, and has become a very common procedure to evaluate the integrity of drilled shafts. Recent advances include 3-D tomography.

SPECIALTY STRESS-WAVE CONFERENCES

An ongoing series of dedicated conferences on dynamic pile testing provides a continuing history of dynamic testing methods. Significant accomplishments since the conference's inception are well documented and chronicle the improvement in both methods and equipment. The proceedings confirm the acceptance and document the growth of the use of these testing and analysis tools. These conferences started with the International Seminar on the Application of Stress-Wave Theory to Piles held on June 4 and 5, 1980, in Stockholm, Sweden. Edited by H. Bredenberg from the Swedish Royal Institute of Technology, the 344-page proceedings contains 24 technical papers and discussions by contributors from 11 countries (Bredenberg, 1980). The main topics were: stress-wave theory, measuring techniques and equipment, prediction of driveability and bearing capacity, and integrity of piles.

Organized by the Swedish Pile Commission, the Second International Conference on the Application of Stress-Wave Theory to Piles was held again in Stockholm on May 27-30, 1984. The 452-page proceedings (Holm et al, 1984) contained 54 papers by authors from 16 countries. The main topics were: bearing capacity, integrity of driven and cast-in-situ piles, drivability and evaluation of subsoil pile driving parameters, dynamic-static pile-soil behavior, hammer performance, field measuring equipment, production control and monitoring, computer simulation of pile driving, and special applications of stress wave based methods. There was also a companion 158-page book containing the notes from two special lectures on stress wave theory and measurements (Fischer and Rausche, 1984).

The Third International Conference on the Application of Stress-Wave Theory to Piles (Fellenius, 1988) was held in Ottawa, Canada during May 25-27, 1988. B. H. Fellenius organized the conference and edited the 924-page proceedings which contain 86 technical papers from 21 countries. The conference was sponsored by the International Society for Soil Mechanics and Foundation Engineering and the Canadian Geotechnical Society.

The Fourth conference was held in The Hague, The Netherlands (Barends, 1992) during September 21-24, 1992. F.B.J. Barends edited the 720-page proceedings containing 97 contributions from 21 countries. The Fifth conference, organized by the University of Florida, was held in Orlando, Florida, USA during September 11-13, 1996. Edited by F. Townsend, M. Hussein, and M. McVay, the 1185-page proceedings archive the 100 papers by contributors from 27 countries (Townsend et al, 1996). The Brazilian Society for Soil Mechanics and Geotechnical Engineering organized the Sixth conference (Niyama and Beim, 2000), held in Sao Paulo, Brazil during September 11-13, 2000. The 772-page proceedings contained 100 papers from 24 countries. This year (2004), the Seventh in this successful series of specialty "Stresswave" conferences devoted to the application of stress-wave theory to piles will be held in Petaling Jaya, Selangor, Malaysia.

During this 24-year period there have been more than two million dynamic pile tests performed worldwide. These seven reference works form the backbone of literature on this subject, and demonstrate the worldwide acceptance and application of these cost-effective methods.

Other conferences offered sessions and presentations on stress wave applications to piles. During the 1969 ASCE Annual Meeting in Chicago, the newly formed Deep Foundations Committee presented two sessions; one of them was on "Use of the Wave Equation for Analysis of Pile Driving". During the 1983 ASCE Convention in Philadelphia, Pennsylvania, USA, George G. Goble organized "Symposium 6 – Dynamic Measurements of Piles and Piers"; Goble (1983) also edited the proceedings containing 14 papers (by contributors from seven countries) equally divided into two groups: Professional Experience and Case Studies, and Design Considerations and Pier Integrity Evaluation.

STANDARDS AND SPECIFICATIONS

Standard specifications, codes, and practice guidelines in effect in many countries worldwide cover dynamic testing and evaluation of deep foundations based on stress-wave theories and measurements. In the United States, these include:

- ASTM D-4945 Standard Test Method for High-Strain Dynamic Testing of Piles.
- ASTM D-5882 Standard Test Method for Low-Strain Integrity Testing of Piles.
- ASTM D-6760 Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing.
- ASCE Standard Guidelines for the Design and Installation of Pile Foundations.
- PDCA Recommended Design Specifications for Driven Bearing Piles.
- AASHTO T-298 Standard Methods of Test for High-Strain Dynamic Testing of Piles.
- International Building Code (ICC) Pier and Pile Foundations Load Tests.

Similar standards, specifications, codes, and guidelines have also been adopted in Australia, Brazil, Canada, China, France, Germany, Great Britain, Mexico, Norway, Sweden and other countries. Many others also utilize stress-wave based testing and analysis methods based on general practice without the benefit of regulation by standards and codes.

FUTURE OUTLOOK

Undoubtedly, the 21st century will witness continued Civil Engineering developments worldwide at an accelerated pace. In addition to conventional construction to accommodate the natural population growth, there will be "mega-projects" that were unthinkable not long ago due to technical reasons. Most will require deep foundations systems with marked demand for economy and high performance.

Already, we see advancements in high-strength steel, high-performance concrete, new piling materials, large size driven piles (recently, concrete pipe piles 40 feet in diameter were installed in China) and drilled shafts, advanced installation equipment, automated testing systems, remote monitoring technology, and a scientific approach to deep foundation geotechnical/structural design and analysis methods and procedures. The application of stress-wave theory for pile testing and analysis will continue to be the method of choice for the future testing of deep foundations.

New remote testing technology utilizing digital data transmission by cell-phones or satellite promises the widespread availability, convenience, quick response and cost effectiveness for real-time monitoring of the installation and testing of deep foundations. Based on higher loads and better design methods, new procedures such as LRFD (Load and Resistance Factor Design) have been developed to reduce the risk of failure.

The foundation cost can also be lowered through more testing since the foundation performance is then known. Within the coming decade, due to the increased reliability of these dynamic methods of geotechnical capacity and structural condition determination, and the decreasing relative cost of the testing, it will be practically and economically feasible, desirable, and possibly even required to test every driven pile and cast-in-place shaft for structural quality and geotechnical capacity.

For the near future, most of the advances in the application of stress-wave theory to piles are likely to be in novel applications and innovative automation, rather than the innovation in the fundamental analytical tools. The technology employed in dynamic pile testing and analysis is among the most advanced in the field of civil engineering today.

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APPENDIX

Deep Foundations Landmarks

To place the early development of the application of stress-wave theory to piles in historical context, this section briefly lists what is believed to be the dates of some major piling developments in the 19th to mid-20th Centuries:

- 1802 - John Rennie first to utilized steam power in pile driving in England
- 1835 - Cast-iron pipe piles first used in England
- 1839 - First documented full-scale pile loading test in New York, USA
- 1843 - Steam-powered hammer by the Scottish inventor James Naysmyth
- 1846 - Clarke, Freeman and Varley introduce a compressed-air hammer in England
- 1865 - Wood piles were treated by creosote in Somerset, Massachusetts, USA
- 1887 - Vulcan Iron Works developed a steam hammer in the United Sates

- 1888 - *Engineering News* pile driving formula
- 1893 - First application of hand dug large caissons in Chicago, USA
- 1893 - Mckiernan-Terry builds first double-acting steam hammer, USA
- 1896 - A. A. Raymond used the first cast-in-place concrete pile in the USA
- 1896 - First precast piles by Hennebique in France
- 1908 - A. A. Raymond first used precast concrete piles in Chicago, USA
- 1908 - Bethlehem Steel Company introduces steel H-piles, USA
- 1908 - E. Frankignoul invented the Franki driven-tube pile in Belgium
- 1910 - Raymond Company replaces wood pile driving leads with steel leads
- 1910 - First documented full-scale static loading test on a caisson in Chicago
- 1913 - American Society of Civil Engineers forms the first Foundations Committee
- 1925 - Karl Terzaghi publishes the first book on soil mechanics Erdbaumechanik
- 1926 - Delmag company in Germany invents the air-Benzolmixture explosion hammer
- 1938 - Delmag company in Germany invents the diesel hammer
- 1931 - Hugh B. Williams of Dallas, Texas builds mechanical augering machines later used for drilled shafts
- 1939 - Prestressed concrete piles used first in Sweden
- 1948 - Edward A. L. Smith introduces the wave equation computer analysis program
- 1950 - First planned use of drilled shafts by a State DOT bridge in San Angelo, Texas
- 1956 - Raymond Patterson granted a USA patent for hollow-stem auger-cast piles
- 1961 - First vibratory pile hammer built in the USA
- 1963 - Raymond International, Inc. introduced the first hydraulic hammer in the USA
- 1968 - First electronic dynamic pile testing system developed at Case Institute of Technology in the USA
- 1968 - American Society of Civil Engineers forms the Deep Foundations Committee
- 1977 - First drilled shaft design manual by FHWA