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Introduction and a Brief History

1.1 INTRODUCTION

Nondestructive Testing (NDT) for deep foundations is very much an expression of the state-of-the-art of the electronics and computer industries, materials science and our ability to bring them together and put them all to practical use. All three of these crucial areas have seen tremendous advances in the last ten years. This book is not intended to supplant any of its forebears, but rather to build on their foundation (no pun intended!) by reminding the reader of the origins of the techniques (and the assumptions made at the time!) and bringing the reader up-to-date with the enormous gains that our industry has recently made; hence, a suitable subtitle for this book – ‘Another Decade of Technical Advances’. The decade in question started with the publication of the Federal Highway Administration (FHWA) report ‘Drilled Shafts for Bridge Foundations’ (Baker *et al.*, 1993). This report was the essential key to acceptance of NDT techniques for drilled shafts and augered, cast-in-place (ACIP) piles in the United States, which in turn increased the acceptance and use of both drilled shafts and ACIP piles as reliable foundation techniques. It is a fact that engineers in many countries were schooled in the USA and look to the engineering community in the USA for guidance. The FHWA report thus had a significant effect on both the testing community and the deep foundations industry worldwide. It is, at the time of writing this book, still the international benchmark for many testing specifications.

Nature has regularly taken its toll of the works of man through unexpected catastrophes, ranging from flooding to earthquakes to volcanic eruptions. Rivers in flood scour away the soil supporting bridge piers – sands beneath high-rise buildings behave like a liquid when an earthquake strikes – glaciers on high volcanoes melt in minutes during an eruption, triggering devastating mudslides that spread for miles. Each natural event reminds us that the stability of the soil cannot be taken for granted

and that deep foundations must often be designed to do much more than to simply support the mass of the structure built upon them.

In addition to this, population growth and commercial expansion create pressures that demand higher buildings and larger structures with each succeeding generation. This increases the need for deep foundations, often in less than ideal geotechnical and physical conditions. It is to the credit of civil engineers and the deep foundation construction industry that they have always found ways to meet these demands, often using innovative designs, construction techniques and materials. So much innovation is not without its risks, however, and foundation failures have occurred because quality control techniques failed to keep pace with deep foundation technology. Having said that, it must also be acknowledged that it is often extremely difficult to distinguish between foundation failure due to defects in the foundation itself, and failure of the surrounding soil or bearing strata. Notable examples are discussed in more detail later in this chapter, under the subheading 'Deep Foundation Failures and NDT'. Unfortunately, corruption and deliberate malfeasance are also sometimes factors in the creation of substandard foundations – the nature of the problem is then indisputable, but the actual cause becomes clouded in 'finger-pointing' and legalities.

Thus, the forces of nature and the needs of mankind have created a demand for both deep, stable foundations, and for quality control techniques that can ensure their reliability. Proof testing of each and every foundation by static loading to twice the maximum probable seismic or catastrophic load is a practical and financial impossibility, yet owners and engineers alike are reluctant to accept something that they cannot see without some form of assurance that it is sound, and will perform as designed. It is a basic truth that 'necessity is the mother of invention' – and never more so than in this case. Non-invasive and/or nondestructive alternatives to full-scale tests were developed specifically to assess a foundation's integrity and/or predict likely performance without raising project costs to prohibitive levels.

NDT of deep foundations is a complex topic covering a number of different techniques designed to gain information about the integrity and quality of the material that makes up a deep foundation. Typical foundation materials are concrete, timber, steel and rock. Deep foundations vary in size and shape, may be constructed of a combination of materials and may be built by a combination of several different techniques. Each combination of size, shape, material and construction method creates a unique set of circumstances that includes the risk of a variety of defects specific to those circumstances. Those same circumstances will determine the accessibility of the foundation for inspection during construction and for NDT examination after construction.

The variations in possible defect types, foundation access and construction material have led to the development of several different NDT methods over the last 30 years. Each method has been designed for a specific purpose and a defined range of circumstances, and therefore has a specific and unique set of capabilities that determine its applicability to a particular project. Conversely, each method also has a specific set of limitations that may adversely affect its effectiveness or the reliability of the data

generated under certain circumstances. Using a test method that is inappropriate for a given set of circumstances or for the information that is being sought will, at best, be inconclusive, and at worst may be actively misleading (Stain, 1982).

In order to be able to specify an appropriate method or to recognize an inappropriate specification, it is necessary for the engineer, specifier and/or contractor to not only understand the capabilities and limitations of each of the methods in use today, but also to be aware of the potential problems for both construction and testing that are inherent in each type of foundation and in the local soils. This manual therefore describes the most commonly used deep foundation construction techniques, the limitations imposed by the local soils, typical use of materials and the NDT methods commercially available at the time of writing. It also aims to increase the reader's understanding of these factors by providing an overview of the principle types of deep foundation, a brief history of the development of NDT, a description of the various NDT methods and a summary of the capabilities and limitations of each method.

1.2 A BRIEF HISTORY OF DEEP FOUNDATIONS AND THE ADVENT OF NDT

1.2.1 CAVEAT AND ACKNOWLEDGEMENT

The authors of this book recently participated in the writing of a manual for the inspection of drilled shafts, sponsored by the Deep Foundations Institute. This work included the preparation of a brief history of both high- and low-strain tests. During the course of researching and summarizing the history of these methods, it became apparent that most histories of engineering are, sadly, colored by the culture of the historian in much the same way that the histories of conflicts are colored by the side with which the reporter sympathized.

We are, today, spoiled by the ease of access to knowledge that the Internet provides – it sometimes makes us forget that not all knowledge is yet available ‘at the click of a mouse’. Researchers before the 1980s had no Internet or Worldwide Web and had to rely on old-fashioned footwork and laborious library searches. Sterling work was often published in obscure local or national society publications and rarely received international recognition; being digitized and posted on ‘the Web’ was never even an option. Such work was also often written in a language unfamiliar to other researchers. Small wonder, then, that researchers in any country might be unaware of the achievements of colleagues in other countries and were therefore doomed to ‘reinvent the wheel’ on numerous occasions.

The history reported in this book is a result of the best efforts of the authors and numerous reputable sources to keep the facts straight and unbiased by commercial interests. Much of the research was performed in the old-fashioned way – by personal recall, interview of industry veterans and by library searching. We apologize for any omissions or oversights, which we must attribute to gaps in the collective knowledge

of the industry. By the same token, we do not apologize for any similarities between the history published here and the history published in the DFI manual – history should be history, no matter who recounts it!

1.2.2 THE HISTORY

Since the dawn of civilization, Mankind has been aware of the need for a stable foundation if any substantial structure is to survive for long without settling, cracking or sometimes just falling apart! Often, simply digging through soft topsoil to a stiffer underlying soil and piling up rocks proved adequate. In other cases, particularly in deep sand or alluvial soils, deeper foundations were needed. Nobody really knows who first came up with the idea of stripping a tree-trunk and banging it into the ground, but driven timber piles have been around almost as long as people have lived in constructed homes. When the ancient Roman Empire was at the height of its splendor, driving of timber piles was already regarded a documented science. Recent historical research sponsored by American Piling Equipment was published by the Deep Foundations Institute in the *Deep Foundations* magazine (Smith, 2005). According to Smith, the oldest bridge built by the Romans was the *Pons Publicius* (Bridge of Piles), constructed by Ancus Martius in or about 621 BC. Unfortunately, Smith is not clear as to whether it was truly the oldest Roman bridge or merely the oldest Roman bridge still in existence.

While some of the ‘science’ appears primitive and flawed by current standards, Smith shows that the subject of timber pile foundations had been thoroughly examined and documented by Marcus Vitruvius Pollio (Vitruvius) in his *De Architectura, The Ten Books on Architecture*, believed to have been written between 27 and 23 BC. Vitruvius not only wrote about the appropriate design of timber piled foundations, but described the proper method of harvesting the timber to ensure longevity, and discussed why some species of timber last longer than others. His theories as to the cause of the difference in rot resistance of the various species may appear laughable to a modern scientist, but demonstrate that the Romans were clearly aware of the fact that timber driven below the ground water table lasts considerably longer than timber exposed to the atmosphere. Julius Caesar, in his book on the Gallic wars, *De Bello Gallico*, described the installation of inclined piles to resist river current forces during the construction of a bridge over the River Rhine near Koblenz in 55 BC. The reader interested in the history of driven piles before the electronic era will find many gems of knowledge about the subject handily condensed in Smith’s article.

In more recent times, greater loads and the need to build on more difficult soil conditions (not to mention a shortage of suitable trees in some areas!) created a need for alternative approaches, and deep foundations evolved through the early hand-dug concrete caisson and the driven steel pile to the current range of alternatives – drilled shafts, displacement shafts, pre-cast concrete piles, steel piles of various configurations and augered, cast-in-place piles.

The history of nondestructive test methods for deep foundations is almost as hard to pin down as the history of deep foundations themselves, but one thing is certain – development of NDT occurred along parallel paths in several different parts of the world. The present state-of-the art is a result of knowledge and experiences shared at international conferences sponsored by such groups as the Deep Foundations Institute (DFI International), the International Association for Foundation Drilling (ADSC-IAFD), the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), and in research projects sponsored by professional or government bodies, such as the Federal Highways Administration (FHWA) in the USA, and various European Departments of Transportation or construction industry research centers, such as the Centre Experimentale de Recherche et d'Études du Bâtiment et des Travaux Publics (CEBTP) in France, The Netherlands Organization (TNO) in Holland and the Federal Institute for Materials Research (BAM), Berlin, Germany.

The scientific principles behind some modern test techniques can be traced back to Victorian times. A graduate student at Northwestern University, Illinois, USA, while completing a literature search for his Ph.D. dissertation on the 'Frequency Equation for Cylindrical Piles Embedded in Soil' (Hannifah, 1999), found two 19th Century wave-propagation research references, one of which dates back to 1876 (see Chapter 13 – Current Research: Guided Waves).

By the mid-1950s, it was well-established that the propagation velocity of a stress wave through concrete was a function of the modulus and density of the material, and researchers had begun to look at ways of using stress waves to assess the quality and integrity of deep foundation shafts. While the theory seemed simple enough, electronic technology lagged far behind the researchers' needs, and stress-wave measurements proved very difficult to put into practice outside of the laboratory.

The first published reference to measurement of high-strain stress waves in a driven pile was made in England in 1938 (Glanville *et al.*, 1938), but it was more than 20 years before practical applications for high-strain stress-wave measurements were developed. The breakthrough research was conducted more or less concurrently by teams at Case Institute of Technology (now Case Western Reserve University) in the United States, and the building research division of the Dutch Technical Research Institute, The Netherlands Organization (TNO) in Holland.

In Europe, the Dutch first discussed high-strain measurements in TNO's in-house publication 'TNO Rapport' (Report). TNO Report Number 341, published in 1956, described stress-wave measurements during the driving of three piles for Jetty No. 1 in the Rotterdam Harbor project (Verduin, 1956). At about the same time, an article which discussed what occurred in the soil during pile driving was published by De Josselin De Jong in *De Ingenieur*, a Dutch-language engineering publication (De Josselin De Jong, 1956). Henk Van Koten led much of the TNO research at that time, and published a paper on stress-wave propagation in a driven pile in 1967 (Van Koten, 1967).

According to the recollections of the Case team, divulged in personal correspondence with the authors during the preparation of this book, the development of

high-strain stress-wave testing in the USA began with a 1958 Master's Thesis by a student named Eiber at Case Institute of Technology, in Cleveland, Ohio. This thesis led to the establishment of an extensive research project under the direction of Dr George Goble with funding by the Ohio Department of Transportation and the United States Federal Highway Administration (FHWA). Started in 1964, the Case team's research determined that both strain and acceleration measurements at the pile top were necessary for dynamic pile analysis. Early measurements were recorded on oscillographs, which used tiny mirrors mounted on electrical armatures that were driven by the input signal, to reflect a narrow beam of light onto photosensitive paper. By 1970, high-accuracy magnetic tape recorders were available to record the data.

The real-time analysis, termed the 'Case-Goble Method', is named after the University and the Research Director (Goble, 1967; Goble *et al.*, 1975), while the more extensive numerical analysis CAPWAP (Case Pile Wave Analysis Program) is a modeling technique that uses the high-strain measurement data to determine the dynamic response of the soil (Rausche *et al.*, 1972).

The Case researchers were limited by the technology of the day, just as the TNO team was, and practical equipment became commercially available at about the same time in both Europe and the United States. Goble and his associates from Case formed Pile Dynamics Incorporated and developed their first commercial equipment in 1972. The earliest equipment for on-site recording and analysis relied on analog computers. Digital computers became generally available both in Europe and the United States in the early 1980s. Current equipment for NDT of foundations is based on either PCs or hand-held computers, and in some cases data can be transmitted via modem or cellular telephone from the construction site to the engineer's office in a matter of minutes after completion of testing. This progression of capability reflects the growth in electronics technology over the past two decades.

Although high-strain dynamic pile testing was developed initially to determine bearing capacity and/or hammer efficiency, it was quickly realized that evaluation of driving stresses and identification of pile damage also provided valuable information. These features were soon incorporated as a standard part of the pile-driving analysis procedure. In 1974, researchers began to consider application of these techniques to drilled shafts.

The low-strain Impulse-Echo (or Sonic-Echo) test was developed in the 1960s. One of the leading researchers to explore the capabilities and limitations of the Impulse-Echo method was Jean Paquet, of the Centre Experimentale de Recherche et d'Études du Batiment et des Travaux Publics (CEBTP) in St. Rémy-les-Chevresuses, France. The CEBTP is the research institute established by the federation of the construction industry in France and is primarily concerned with construction quality control. Paquet was a prodigious researcher who simultaneously directed research and development programs concerning high-strain, low-strain and ultrasonic testing of deep foundations, plus allied programs concerned with developing the software for analysis of the data from these methods. The technology of the time made the Impulse-Echo method difficult to apply in the field, and it was not commercially available until 1974

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in Europe and 1979 in the USA. In both cases, the low-strain Impulse-Echo test was a derivative of the high-strain pile-driver analysis technique.

The earliest versions of the Impulse-Echo test used a hammer impact to generate a stress wave, and an oscillograph, or UV recorder, to record the response of a geophone or an accelerometer attached to the top of the shaft – a painstaking process that required delicate timing and often resulted in a lot of wasted paper. The first major improvement came in the early 1970s, when the phosphor storage oscilloscope replaced the oscillograph. A photograph was taken of the test result on the oscilloscope screen, which still required careful timing and often resulted in blurry images and much wasted film! The next major advance was the advent of the microprocessor and in 1984 TNO researchers announced the first digital version of the Impulse-Echo test (Reiding *et al.*, 1984, Schaap and de Vos, 1984). The USA team followed with its own version in 1985.

The Impulse-Echo test was developed for use on pre-cast, driven piles, and works very well in reasonably soft, uniform soil conditions where shaft length and cross-section are known. However, it is often less conclusive on sites with highly variable soil conditions or on drilled shafts where shaft cross-section can vary due to use of temporary casings or variations in lateral soil stiffness. The effective penetration depth of the method is also limited by the stiffness of the lateral soils.

As the Impulse-Echo test was evolving, other visionaries in the United States also saw the potential for NDT of drilled shafts. One of the more notable was the late John P. Gnaedinger, founder of STS Consultants, Ltd. Gnaedinger developed and patented the G-cell, which consisted of a small steel cell which contained a remote-controlled striker assembly, similar to that in a door chime. The G-cell was installed at the base of a shaft attached to the reinforcing cage. After concrete had been placed and reached a reasonable maturity, a sensitive sound recorder was attached to the top of the shaft and the G-cell striker was activated. An oscilloscope measured the time taken for the stress wave generated by the striker to reach the top of the shaft. Since the stress wave was only traveling one way, instead of down the shaft and then back up again, the G-cell method could potentially be used on shafts twice as deep as those that could be tested by the Impulse-Echo method. Gnaedinger's US patent, 'US 3 641 811: Method and Apparatus for Determining Structural Characteristics', was filed in 1969 and granted in 1972 (Gnaedinger, 1972). No fewer than 14 subsequent applications for nondestructive test patents referenced Gnaedinger's patent.

In 1968, Paquet published a landmark paper that discussed the limitations of the Impulse-Echo method and described the assessment of drilled shafts by the 'Vibration method', in which a swept-frequency vibrator was attached to the head of the shaft and the response monitored by multiple velocity transducers (calibrated geophones) (Paquet, 1968). A major drawback of the method was the amount of preparation required to attach the vibrator and the transducers to the top of the shaft. Paquet was visionary enough to understand the difficulties of applying the Vibration method reliably under actual site conditions and to foresee the development of the Impulse-Response method, in which a hammer blow through a calibrated load-cell would

generate a quantified impulse, and thus allow a network analysis of the shaft response to a known input, even though the electronics at the time were not capable of recording such an event.

In 1974, Paquet applied for a patent on an analysis method that used a Fast Fourier Transform (FFT) of the recorded data into the frequency domain, where velocity was divided by force to provide the transfer function, or mobility signature, of the shaft. It was 1977 before analog computers finally caught up with Paquet, and technicians could make his theory become a reality. Since then, the development of NDT methods has proceeded rapidly. The introduction of digital computers has revolutionized the field, and the Impulse-Response method is now widely accepted throughout the world for the assessment of drilled shafts, locating voids beneath pavement slabs and behind tunnel linings and assessing concrete quality in structures ranging from parking decks to chimneys and storage silos.

The stories of the Cross-Hole Sonic Log (CSL) and Parallel-Seismic methods are similar. These methods were also developed by the CEBTP in the late 1960s (Paquet, 1969; Paquet and Briard, 1976) but were hampered by the technology of the time. The advent of the portable digital computer, and then the PC, made CSL testing an inexpensive reality and it began to be widely used in Europe in the early 1980s. Several countries in Asia and North Africa quickly followed the European lead, largely as a result of French post-colonial influence, but the CSL method was not introduced commercially to the United States until 1986.

Despite widespread use of NDT methods for both driven and drilled shafts in Europe by the early 1980s, NDT for drilled shafts was much slower to be adopted in the United States, Canada and South America. The first use of the CSL method in the Americas was by the present authors in 1986. Drilled shafts were constructed in the Spokane River for the repair of the flood-damaged powerhouse at the Upstream Dam Hydroelectric Project in Spokane, Washington. The construction conditions were extremely difficult because the river was still in flood, and so the owner decided that it would be a good time to try CSL to verify the quality of the foundations. The test immediately proved its value in conditions where no other form of testing was practical.

In 1988, the FHWA and the California Department of Transportation (CALTRANS) sponsored a research program in which a number of drilled shafts were constructed with known defects, and NDT practitioners were invited to test the shafts with whichever methods they chose. The interest created by the project was considerable, and it was extended to include additional shafts installed on a site at Texas A&M University in College Station, Texas. The end result, published in the FHWA Report No. FHWA-RD-92-004 (Baker *et al.*, 1993) was one of the most critical factors in the acceptance of NDT for drilled shafts in the United States. The FHWA report started reaching the desks of State DOT engineers and specifiers late in 1994, and they began specifying NDT methods for quality control by about the summer of 1995. In 1996, the general construction industry started to follow suit, and by the year 2000 the use of NDT for both driven and drilled shafts was almost commonplace in the USA.

The effect of this acceptance of NDT methods went beyond the testing community in most countries. The fact that there is now a number of quality assurance techniques available for drilled shafts, where previously there had been no economically practical method of testing the finished product, has encouraged many engineers to use drilled shafts for projects where they would formerly have preferred to use driven piles. The same has occurred with the use of drilling slurry. Now that the end-product can be closely examined, engineers are more comfortable in allowing excavation and concrete placement under water or slurry, instead of requiring the foundation contractor to adopt expensive multi-casing methods in an effort to seal out groundwater and unstable soils so that concrete can be placed 'in the dry'.

Unthinking reliance on the FHWA report or other similar references, however, can have the effect of 'freezing' the state of the technology. As mentioned in the Preface, the need for this book was illustrated recently by a project in the United States in which the engineer was relying on the FHWA publications. A problem had occurred during the construction of a drilled shaft, which gave rise to the possibility of soil contamination of the concrete about halfway down the shaft. The shaft was not equipped with access tubes for any of the down-hole tests, and so the testing firm for the project recommended a surface reflection technique such as Impulse-Echo testing. The project engineer refused to accept that proposal because the FHWA report gave the impression that surface acoustic methods were only capable of detecting a major defect in a drilled shaft, and the subsequent FHWA publication 'Drilled Shafts: Construction Procedures and Design Methods' (FHWA-IF99-025) contains the recommendation that these methods should not be used as the primary integrity testing method for axially loaded shafts in which the design load exceeds 40 % of the structural capacity. This may well have been the case in 1993, but research and development of test equipment and analysis procedures has continued unabated since then. The ability of the surface reflection techniques to detect smaller anomalies is governed by several factors, including the length/diameter ratio of the shaft, the depth to the anomaly and the type of anomaly. In these authors' experience, anomalies as small as 10 % of the shaft cross-section can sometimes be detected by surface reflection techniques. By blindly sticking to the opinions expressed in the FHWA report, the engineer was refusing to acknowledge several important facts:

- The report was based on data gathered more than ten years ago, from about 1988 to 1991.
- Some of the personnel involved had less than three years experience with the techniques at that time.
- The hardware and signal quality has improved significantly since then.
- Research has continued into better data acquisition and analysis algorithms.

In a more recent Class-A prediction study at the National Geotechnical Experimental Site (NGES) at the University of Massachusetts in Amherst, MA, it was concluded that, in fact, the skill and experience of the operators, coupled with more advanced

equipment, had improved the overall performance of surface NDT techniques to the extent that some of the better participants located defects as small as 6 % of the shaft's cross-sectional area, and multiple defects were accurately located in some shafts. It was conceded, however, that the skill of the operator was crucial to the success of the surface NDT methods (Iskander *et al.*, 2001).

In these authors' experience, and the experiences of other reputable experts in the field of nondestructive testing, the smallest anomaly that can be reliably detected and quantified by the surface reflection techniques is about 10 to 15 % of the shaft's cross-sectional area, depending on shaft dimensions, anomaly depth and soil properties. Whether such an anomaly is significant or not must be judged on a case-by-case basis by an experienced engineer, rather than by the blanket rejection implicit in the 1993 FHWA report.

Most contractors and engineers will readily admit that the feedback provided by NDT has enabled them to refine shaft designs and construction techniques, and modify equipment to improve the quality and reliability of drilled shafts and augered, cast-in-place (ACIP) piles. This, in turn, has increased confidence in drilled shaft and ACIP foundations, and made a significant contribution to the growth of their respective market sectors.

1.3 DEEP FOUNDATION FAILURES AND NDT

Well-documented failures of the shafts of piled or drilled shaft deep foundations in service are rare. Two possible reasons for this are the tendency to 'over-design' deep foundations, thereby reducing risk of failure to a minimum, and difficulty in distinguishing between failure of the shafts and failure of the soil bearing capacity, or indeed, a combination of both. However, the rare reported failures are a warning to the underground industry, highlighting the difficulties in predicting the variables and unknowns present, particularly in water-bearing soils. As the FHWA report (Baker *et al.*, 1993) states, 'this results in a lower risk tolerance for a single or double shaft supported pier compared to multiple piled foundations'. The modern trend indeed is to replace the latter with large-diameter drilled shafts, particularly for large bridge structures in seismic zones.

Some settlement of foundations is expected, and allowed for in the design of the structure. Determining exactly what amount of settlement should be considered unacceptable is problematic, and the amount of settlement that constitutes failure of the foundation is even more contentious. Lessons learned from shaft failures do offer help in avoiding problems in future construction; however, a complete, impartial investigation of deep foundation failure is costly, and therefore rare. Any investigation is usually funded by legal costs alone, and litigation does not necessarily produce a clear picture of the whole story. The first two examples described here are typical of this dilemma.

1.3.1 ESSO OIL TANKS, FAWLEY, HANTS, UK

An oil refinery tank farm was constructed on soft soil conditions in Southern England to accommodate the large quantities of oil being delivered by the supertankers that were built following the closure of the Suez Canal. Compared to existing design practice, the size of tanks required to store the oil arriving at the refinery increased dramatically. One tank failed during water test loading and a second tank showed incipient foundation failure during the start of water test loading. The full story is described in Leggatt and Bratchell (1973) and the Institution of Civil Engineers (UK) (1974) gives a brief description of the events. Driven cast-in-place 420-mm-diameter piles with expanded bases were founded in river gravel through approximately 2 m of gravel fill overlying 6–8 m of soft silty clay and peat. The piles were reinforced to the base, and the casing was withdrawn during concreting. A thickened portion of the 380-mm-thick reinforced concrete raft tank base capped each pile. After tank failure, a tunnel was driven beneath the raft to expose the upper part of some piles. At the location of maximum raft deflection, many piles showed signs of bending overstress, increasing in severity from vertical cracking to complete separation of the pile from the pile cap. In addition, some shafts had visible necking, with exposure of reinforcing steel. Nondestructive vibration testing was performed on 43 of the exposed shafts.

Experts were appointed to examine the failure, representing the owner on one hand and the piling contractor on the other. The experts for the owner claimed defective shaft construction as the cause of tank failure, while the experts for the piling contractor claimed failure of the founding gravel layer as the reason. The case was settled before the end of legal proceedings, with no clear technical agreement on the root cause of the failure.

1.3.2 NEUMAIER HALL, MOORHEAD, MN, USA

The second example concerns a fifteen-story residence hall built in 1969 on an American university campus. The following case history emerged from research on the Internet. The building was constructed using lift-slab architecture, with reinforced concrete floor slabs carried by steel columns. These columns were in turn supported by concrete caissons (drilled shafts) extending 30 m down through the clay subsoil, terminating in bell-shaped bases drilled into dense glacial till below. After construction, the north-west corner developed large cracks in the foundation and on interior and exterior walls. These cracks were the result of differential settlement of the foundation and partial rotation of the building, which exceeded 75 mm in certain areas. The settlement was believed to be induced by overstress of the caissons, possibly due to negative skin friction as a result of a lower water table, loss of integrity of the caissons due to necking or contamination of the concrete and a complete structural

failure of the caisson shaft. One of the unique observations is that the caisson in the north-west corner, despite complications during its construction, had been seemingly immune to these effects, and had settled within the expected limits. Due to concern that the strain on structural components could lead to failure of the lift-slab architecture, and an estimated repair cost of over one million dollars, the decision was made to close the building and demolish it.

Apparently, the building first began to show signs of foundation problems within ten years of its construction, with foundation columns showing a differential settlement of 25 to 30 mm. Measurements of the site were taken to observe the settling rates, but were complicated by apparent movement of other parts of the structure. Once a stable benchmark was established, all readings began showing a general negative (downward) movement. The continuing stress on the structure as the foundation settled soon became evident. Major cracks and displacements were visible on the north-west corner of the building over the first three stories. Interior foundation walls showed cracks, again in the north-west corner. Several rooms in this corner were rendered unusable because of the extensive cracking; also, windows and doors became non-functional due to the stress. At the fifteenth floor, large horizontal cracks appeared all along the north wall. A maximum differential settlement of nearly 100 mm and a total settlement of more than 125 mm were reached. In addition, much of the stress represented itself in the form of rotation. The entire structure was attempting to rotate about the point of greatest stress. Measurements showed that, in places, the building had deviated from plumb by more than 75 mm. By comparison, the values generated when evaluating the original design load indicated that the expected settlement was in the area of 25 to 33 mm. It is interesting to note that the north-west shaft settled a total of 40 mm, close to the expected amount. A list of possible 'culprits' was created:

- Settlement of the hard glacial till (hardpan).
- Settlement of the clay sands above 30 m.
- Settlement of disturbed material at the bottom of the caisson bells, caused at the time of construction.
- Structural compromise of caissons.

The first to be considered was hardpan settlement. The hardpan is composed of glacial sandy-gravelly till. The recorded standard penetration N value for this material under the structure was 50. For that N value, a settlement of 125 mm is not a realistic probability.

The second consideration was settlement of the clay sands above 30 m. The elevation of the bases of the shaft bells was also brought into question. They must be located on the correct bearing stratum in order to support the structure. If the shafts had not been drilled deep enough, that could perhaps account for the settlement. The glacial till had been designated as the bearing stratum for Neumaier Hall, and a study of the numerous geotechnical test borings performed on the site showed that the bearing strata was encountered at about 30 m depth. Shaft construction records showed that the shafts were founded at or below this level.

A third possibility was settlement of disturbed material at the bottom of the shaft bells, caused at the time of construction. It could not be determined from the construction records or the inspector's reports if there actually was disturbed material at the bottom of the bells. Calculations, however, showed that any settlement caused by disturbed material at the base of the shafts would have taken place rapidly, and not exhibited the long-term behavior that was recorded on this site.

The fourth consideration was structural inadequacy of the drilled shafts. It is quite possible that several unrelated deficiencies, none of which would be significant by itself, could occur in the same shaft, where the combined effect would result in a significant reduction in shaft capacity. The following scenarios have been well documented and could combine to cause failure of the shaft:

- If the temporary casing is removed too rapidly, the concrete within the casing can 'arch' or lock itself into the casing, thus causing it to be lifted with the casing, which creates suction that may draw soil and water into the concrete, hence resulting in a reduction in cross-section, or 'neck-in'.
- Similarly, if the temporary casing is removed too late, after the concrete has begun to set, the same scenario can occur – some or all of the concrete is lifted with the casing, thus creating a discontinuity in the shaft and a suction that draws soil and water into the resulting void(s) within the shaft.
- The handling and mixing process, particularly if water is added at the site to make the concrete more workable, can affect concrete strength.

A fifth possibility was negative skin friction on the shaft caused by consolidation of the surrounding soils. A significant reduction in the ground water table was recorded on the site, hence causing considerable consolidation of the soil. One of the engineering companies that investigated the failure later calculated that the down-drag or negative skin friction caused by the soil consolidation could have caused the loads on some shafts to be 170 % of the designed capacity. The original design for the caissons anticipated a load of 0.7 MPa. The total down-drag loads plus structural loads were calculated to be between 0.97 and 1.38 MPa at the bottom of the shaft bells. Since a load of more than 2 MPa would have been necessary to cause the 75–125 mm settlement in the glacial till, it is highly probable that a reduction in either shaft diameter or concrete quality occurred, which raised the stresses in that part of the shaft to the level required to cause failure.

1.3.3 TAMPA CROSSTOWN EXPRESSWAY, TAMPA, FL, USA

Some widely reported foundations failures are clearly proven to be failures of the supporting soil and therefore a result of inadequate site investigation prior to designing and constructing the foundations, but the distinction is rarely made in the public media. A very recent example is the settlement of highway viaduct foundations in Tampa, Florida, USA.

An elevated reversible-lane tollway built was being built in the median of the Lee Roy Selmon Crosstown Expressway. When the launching gantry for the deck segments was being positioned on Pier No. 97 on April 13, 2004, the pier sank 11 ft into the ground. A subsequent investigation found that the soil conditions at the pier location were inadequately defined before the design was completed. News media reported that the normal procedures for the local area had been followed, which included drilling an exploratory borehole at each pier location. Unfortunately, the borehole at Pier No. 97 apparently encountered only a limestone pinnacle or ledge, rather than a solid bed. Once the load of the launching frame settled on the pier, it forced the pier to 'punch through' the limestone into the surrounding soft sediments. Two 150-ft sections of roadway buckled as a result.

A few months later, on July 6, 2004, Pier No. 99 settled 1.3 in, which was beyond the acceptable limit of 1.0 in. While an official report on the subsequent investigation has not been released at the time of writing this manual, local news media reported that, of 215 piers, excessive settlement was believed to have occurred on a total of 154.

1.3.4 YUEN CHAU KOK, SHATIN AREA 14B, PHASE 2, HONG KONG

Regrettably, it is not just accidental omission or misfortune that causes problems with deep foundations. It seems to be a universal truth that foundation contractors are among the most 'at-risk' contractors on a construction project, largely because they are dealing with subterranean conditions that are often poorly documented and full of surprises. That fact often combines with the widespread propensity for accepting the lowest bid as the most appropriate bid, regardless of qualifications, to leave the foundation contractor struggling against unforeseen conditions with a minimal budget. This sometimes puts foundation contractors in such a financial bind that one or two of them resort to 'fraud' in order to get paid. Such a case was recently publicized by the Hong Kong Housing Authority (HA) on its Internet website (Hong Kong Housing Authority, 2000).

The report publicizes the findings of a panel that was convened to investigate the circumstances that caused excessive foundation settlement and led to the forced demolition of two partly completed buildings of more than thirty stories. According to the HA report, a foundation contractor that was prequalified with HA won a contract for constructing large-diameter bored piles and installing driven piles on the Yuen Chau Kok, Shatin Area 14B housing project, Phase 2. The project involved the construction of deep foundations for two forty one-story apartment blocks, three thirty three-story blocks and a car park/ancillary facilities building. The large-diameter foundation shafts for the tower blocks were designed to be founded on competent bedrock, with appropriate under-reams, or 'bells'. Unknown to the HA, the winning foundation contractor subcontracted the large-diameter drilled shafts to another contractor who apparently did not meet the requirements for prequalification with HA.

Alerted by excessive settlements that had been reported on foundations on other HA projects, the HA decided to monitor the settlement of foundations on all sites, including the Shatin project. Excessive settlement was recorded at Shatin as the tower block superstructures evolved, becoming so severe that the project was halted when the towers had reached about thirty stories. The settlement continued, and the tower blocks were eventually deemed unsafe, and demolished. Forensic examination of the foundations by full-depth core-drilling showed that, out of thirty six shafts on the site, fifteen were founded short of bedrock by up to 1 m, ten were between 1 and 5 m short of bed rock, and eleven were between 5 and 15.4 m short! Only four of the shafts were proven to be founded on the bedrock as designed, and only eight were composed of concrete that met the project's quality requirements. The other shafts showed evidence of 'honeycomb' concrete, steep or vertical jointing and fractures.

After examining concrete volumes and steel lengths delivered to the site by reputable firms with robust quality control systems, the Enquiry Panel considered the difficulty of disposing of or re-routing substantial quantities of steel and concrete without attracting attention. The Panel also concluded that the foundation contractor had most likely drilled the full depth of most shafts, but did not use temporary casing over the full length, as required in the specification. The Panel also concluded that the sidewalls of the shafts collapsed early in the concrete placement process, and the concrete simply filled the voids created by the sloughing soil – thus, the shafts ended up with substantial 'neck-ins' or total discontinuities.

The Enquiry Panel found compelling evidence of fraud on the part of the foundation contractors. The Panel noted that inspection of the shafts by Cross-Hole Sonic Logging (CSL – see Chapter 10 of this book) had been specified, but the majority of the CSL access tubes had been deliberately 'blocked' to hide the fact that the shafts either contained significant defects or were shorter than the designed length. As a substitute for the inconclusive CSL testing, the foundation contractors offered vibration test data instead (see Chapter 8 – Impulse-Response testing). Unfortunately, the responsible engineer for the HA was unaware of the limitations of the Vibration test and was also unaware that most of the test data were in fact from an adjacent structure, fraudulently presented as being from the structures in question. Finally, when core samples were demanded from the shafts, it is apparent that the HA made the mistake of letting the foundation contractors engage and supervise the core drillers. The Enquiry Panel determined that, in several cases, multiple shallow cores were drilled and then 'doctored' by the foundation contractors to form a composite core that was presented as being from the full length of the shaft in question.

The Enquiry Panel found that the contractors had deliberately obstructed the performance of the tests, manipulated the testing companies and faked both physical and nondestructive test results in order to gain approval for the shafts in question. The enquiry revealed that the subterfuge and collusion had gone unnoticed for so long because the foundation contractors repeatedly worked late into the night, long after the HA inspectors had left the site for the day.

Lack of adequate inspection obviously played a significant role in what could have turned out to be a major fatal disaster had the excessive settlement not been noticed early in the project. It is stated in the HA Enquiry report that there had been too much bureaucratic reliance on correct paperwork, and not enough actual on-site inspection. The reliance on properly completed paperwork generated a false sense that quality assurance was well under control. Similarly, it is implicit in the report that most of the faked NDT data would have been discovered much sooner had the inspectors and engineers in question been more conversant with both the construction technique and the capabilities and limitations of the NDT methods used.

Fortunately for us all, most foundation contractors are conscientious and skilled specialists, but the salutary lesson to be learned from the HA experience is that nothing can be taken for granted, even though all of the paperwork seems to be in order. No amount of paperwork can substitute for conscientious and experienced inspectors, supported by a carefully designed program of nondestructive testing performed by competent field personnel and analyzed by experienced specialists.

1.4 DEFICIENCIES IN EXISTING FOUNDATIONS

Integrity testing of deep foundations as a quality control tool is intended primarily to reduce the number of defective shafts and does not address the geotechnical behavior of the foundation, although the Sonic-Mobility test does offer some insight into soil conditions by the measurement of dynamic stiffness. These present authors have tested foundations beneath demolished structures some years after their construction. Shaft defects discovered at this time in several cases were attributed to built-in deficiencies at the time of construction and not at demolition. Three examples stand out in this group.

The first is a chemical refinery destroyed in an explosion that removed all above-ground structures, leaving the foundation pile cap bases intact. As part of an attempt to assess the viability of rebuilding the plant, the piled foundations were tested non-destructively through the reinforced concrete bases. Each pile cap had three to four 450-mm-diameter driven cast-in-place piles, and the NDT failed to locate 20 % of the piles through the bases. NDT inadequacy was suspected and the bases with no pile response were excavated to reveal that the concrete in the shafts at their junctions with the pile caps was partially or totally missing! These defects had not stopped the structures operating successfully for at least twelve years.

The second example, a multistory parking garage demolished fourteen years after construction to make way for a new high-rise office building, affords a second example of defective shafts beneath structures previously in service. The foundation system comprised evenly spaced 900-mm-diameter bored piles (drilled shafts) linked by ground beams. It was hoped that most of these piles could be incorporated in the new structure design and their heads were exposed for nondestructive testing. The authors performed NDT on the shafts to evaluate their suitability for re-use. A number of

these piles showed considerable necking in the upper 3 m of their shafts and were excavated for visual assessment. Some shafts had no concrete for at least 50 % of their cross-section, over lengths up to 2.5 m. Again, the parking garage had performed with no problems for fourteen years.

The third example is a utility chimney that collapsed during liner cleaning work. The cause of the collapse was believed to be a large mass of flyash that became dislodged all at once, falling several hundred feet to the bottom of the liner, where its kinetic energy was deflected radially outward in an explosive manner, effectively cutting the chimney away from its foundation. Since the foundation slab appeared to be relatively undamaged, the present authors were called in to evaluate the piles supporting the slab to determine their suitability for re-use if a new chimney was to be built on the existing foundation. Once again, several shafts could not be detected by impulse testing from the surface and were physically investigated by excavation along the edges of the foundation slab. In three cases that were investigated, the corrugated steel permanent casing was cut open and the joint between the top of the pile and the underside of the slab was found to consist of unbonded gravel to a depth of several inches. Prior to the structural failure of the chimney, the foundation had shown no signs of excessive or differential settlement.

These cases support the contention that there is considerable 'over-design' in many deep foundations. However, they should not be interpreted to mean that it is not important to control the quality of deep foundations, both from the viewpoint of cross-sectional integrity and material quality. These examples also raise the question of what constitutes an unacceptable defect. Joram Amir, of PileTest in Israel, has made several presentations at Deep Foundations Institute seminars and other geotechnical engineering venues (e.g. Amir, 2002) in which he recommended that anomalies identified by nondestructive test methods should be classified according to severity:

- Anomaly – this could be just an anomaly in the test data caused by the equipment (noise, etc.), the means of access (e.g. access tube debonding) or site circumstances (electrical interference, noise, etc.).
- Flaw – an imperfection or irregularity of shape or material, but not significant in terms of shaft capacity or durability.
- Defect – affects the bearing capacity or the likely durability of the shaft. Engineering evaluation is required – perhaps the shaft can be accepted at a reduced capacity?

The present authors agree with Dr Amir's recommendation. It should be the testing company's responsibility to evaluate the first possibility. Before attempting any analysis, the testing company should verify that the anomaly was not caused by an equipment malfunction, operator error, site circumstances or data-storage problem. Depending on the test method in use, this may be as simple as repeating the test two or three times and then comparing the results. Once equipment or application anomalies have been eliminated, only then can the anomaly be considered a real flaw in the shaft and investigated further to assess its nature, location and significance. Techniques, such as tomography, core drilling or excavation, may be required to provide definitive

information. If the flaw is proven to exist, the geotechnical and structural engineers together should assess its significance, taking into consideration its nature, size and location within the shaft. If it is considered likely to cause an unacceptable reduction in shaft capacity and/or durability, then it should be considered a defect and therefore a reason to reject the shaft until it has been remedied.

Universal acceptance criteria for situations such as these would go a long way towards standardizing test methods, analysis of test data and reporting procedures. At the time of writing this book, the Testing and Evaluation Committee of the Deep Foundations Institute is in the process of creating a document that could include a general consensus guideline for drilled shaft acceptance criteria based on the results of Cross-Hole Sonic-Logging tests and a sample specification for engineers and owners to use (see Chapter 10 of this book for more details).