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THE EVOLUTION OF DEEP FOUNDATION QUALITY MANAGEMENT TECHNIQUES IN THE UNITED STATES

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ABSTRACT

The development and acceptance of quality control and assurance techniques for deep foundations in the United States is a relatively recent phenomenon, and one whose progress can be attributed to a handful of key individuals who first recognized the early promise of these methods, and worked diligently to validate them.

The judicious use of nondestructive testing combined with various methods of full-scale load testing has been a major factor in the growth of the drilled shaft and augered, cast-in-place pile industry, by simultaneously allowing engineers to assess and adjust design assumptions, and allowing contractors to improve construction techniques and equipment. Such quality management programs have also justified significant increases in the allowable bearing capacities stipulated in building codes, particularly in Chicago and the Midwest.

This paper reviews the evolution and acceptance of quality control and quality assurance methods in the United States, and the effect they have had on deep foundation design and construction, and building code requirements nationwide.

INTRODUCTION

The use of driven timber piles for deep foundations can be traced back to the days of the Roman Empire. Several Roman authors of note described the installation of piles. An article published in the Deep Foundations Institute magazine “Deep Foundations” in 2005 discussed the Roman technology in some detail (Smith, 2005). Quality control consisted of striking the top of the pile with a drop-weight until it had either penetrated the ground to the required depth, or simply stopped moving. From Roman times to the 19th century, there was little change in the technology of deep foundation construction, other than the substitution of steel for timber in some 19th century cases. In the early part of the 20th century, the advent of skyscrapers, with substantially greater loads than had previously been encountered, bought about the need for a different approach to foundation design, and the use of hand-dug shafts, or ‘caissons’, and mechanically drilled shafts came into play. Over time a number of proprietary construction methods were developed, using various techniques for excavation stabilization and ground water control. No matter which method was used, they shared one common need – concrete placement in the completed excavation.

Quality control efforts, however, were still limited, consisting primarily of visual observation during construction, and static load testing after construction. Although static load testing provides the engineer with a reasonably accurate idea of the capacity of the shaft tested, the load test set-up takes time and money to construct, and limits the construction activity that may take place in the vicinity of the test rig while the test is being performed. These factors make testing large numbers of shafts prohibitively expensive. Added to this is the natural variability of soils. In some geographical areas a single borehole may accurately represent soil conditions for an entire construction site. In other areas, soil conditions, and particularly bedrock quality, can vary significantly within a few yards. Thus a load test shaft on one part of a construction site may be completely unrepresentative of the shafts on the rest of the site.

The result of these variable factors is that, for many years, deep foundation designers worked with the knowledge that very few of the foundations constructed would actually be proven to be capable of supporting the loads for which they were designed before the design loads were actually applied during construction. Naturally, a conservative approach to design was adopted, and ‘factors of safety’ were often added at several stages in the site exploration and design process. In some areas this practice persists to this day. The author is aware of one relatively recent project where load testing proved the test shaft to be capable of supporting at least 10 times the design load, but the load test jack had reached its maximum capacity before any significant shaft movement occurred, so the true load capacity of the shaft remains unknown. Despite this, the project owners elected to stick with the original design.

Some engineers recognized the costs associated with unnecessary conservatism, and strove to quantify the unknowns that were at the heart of the problem. Karl Terzaghi, generally regarded as the father of soil mechanics, is credited with coining the term ‘The Observational Method’, in which careful observation of all stages of site investigation and foundation construction is coupled with the observer’s past experience and any other available relevant data, providing information that the engineer can use to modify the design and construction process appropriately as the project progresses. The visionary engineers of the mid 20th century that saw the value in the observational method not only applied it in their practice, but demanded better tools to help them quantify the variables. A seminal paper on the subject by a student and protégé of Terzaghi, Ralph Peck, described the advantages and limitations of the observational method (Peck, 1969).

Over the years, the deep foundations industry, geotechnical engineers, and testing practitioners responded to Peck’s challenge in a variety of ways. The advances brought about by the demand for more information fall into three broad categories:

1. Construction monitoring methods
2. Load-testing methods
3. Integrity testing methods

Each category will be discussed in this paper, together with illustrative case histories.

CONSTRUCTION MONITORING METHODS

Construction monitoring methods still heavily rely on visual observation by a competent and experienced inspector, but visual methods are severely limited in deep foundations when temporary casing is used, or when concrete is placed under water or slurry. Fortunately, there is now a steadily growing array of tools to help the inspector during the construction phase of the project.

One of the first was a deceptively simple method of plumbing the top of the concrete column with a tape measure, plotting it on a graph of depth versus volume placed, and comparing it with a graph of theoretical volume versus depth (DFI, 2003). If concrete is placed in relatively small, controlled increments via a skip or bucket in an uncased excavation, this method works well. However, when placing concrete by pump, it is less reliable, because pumps can develop air-locks or miss strokes. Where concrete is placed directly by ready-mix truck, the inspector’s judgment becomes critical, because he or she must estimate how much of the mixer drum’s volume has been placed at any given time. If temporary casings are used, the depth versus volume graph is of minimal value, because soil voids may exist behind the casings that allow the concrete to slump out when the casing is withdrawn.

At the beginning of the 21st Century, inspection technology in common use to assist deep foundation inspectors and geotechnical engineers includes underwater cameras, sonic borehole calipers to determine the shape of a completed drilled shaft excavated under water or slurry (Kort et al, 2007), and the Shaft Inspection Device (SID) attributed to Schmertmann and Crapps in Florida, to permit visual inspection of the bottom of a drilled shaft even under slurry or turbid water, and so aid assessment of likely end-bearing performance (Schmertmann and Crapps, 2002)

LOAD TESTING METHODS

Full-scale load testing of deep foundations has long been the accepted method for verifying design assumptions and foundation quality, both at the beginning of a project, and sometimes during production, as a quality assurance check. Initially, a full-scale load test was accomplished by constructing a large reaction mass (Kentledge) over the foundation shaft that was to be tested, inserting a jack between the kentledge and the shaft, and jacking against the kentledge until the desired load was placed on the shaft. For larger shafts, constructing a kentledge of adequate mass was impractical, and the concept of reaction shafts was born. For this method, one or more pairs of foundation shafts, dubbed reaction shafts, are constructed around the test shaft, and linked by a reaction beam or frame that passes over the top of the test shaft. The load test jack pushes against the frame and the resistance provided by the reaction shafts to apply load to the test shaft. Unlike the kentledge method, which can only be used to assess a shaft in compression, reaction shafts can be used in either tension or compression, and so can be used to assess bearing capacity and/or uplift resistance of the test shaft.

Both the kentledge and the reaction shaft methods have distinct disadvantages, in that there are significant costs associated with preparing and performing them. Not only are there the costs of construction and performance, but, in most cases, performance of a static load test requires that construction activity in the vicinity of the test be reduced, in order to minimize ground vibrations that may affect the validity of the test. This can have a significant impact on project schedule and cost.

In 1987 Jorj O. Osterberg patented a new technique for static load testing, wherein a flat cylindrical hydraulic jack known as an Osterberg Cell, or "O-cell" is attached to the reinforcing cage and lowered into the drilled shaft before concrete is placed. Instrumentation attached to the cell and the reinforcing cage monitors shaft behavior as hydraulic pressure is applied to the cell after the concrete has set, applying load downward into the end-bearing stratum, as well as upward, to mobilize the side-resistance on the shaft. This bi-directional action permits direct evaluation of rock-socket side-resistance behavior versus end-bearing capacity, unlike the top-down loading methods. The O-cell and attached instrumentation are sacrificial, but on completion of testing the jack can be grouted up, thus allowing the test shaft to be used as a part of the new foundation. For very high loads, the O-cell method is inherently safer than building massive kentledge structures or risking failure of reaction beam/shaft connections. At the time of writing this paper, the largest recorded O-cell test stands at 36,000 tons! (Brown, 2010).

A key limitation of all static load test methods is that, for economical application the shaft to be tested must be selected in advance of the construction program. For this and other economic reasons, use of multiple static load tests as a quality assurance measure throughout a construction project is extremely rare. However, since the early 1960's there has been a gradual acceptance of alternative methods for measuring or predicting foundation shaft capacity. The first of these was based on analysis of the response of a pile head while it was being driven by a drop-hammer. The first known reference to measurement of stress waves in a driven pile was by Glanville (1938), but the first practical application of the idea was described for a project in Holland in 1956 (Verduin, 1956). Further development of pile driving analysis in Europe was primarily performed by the Dutch national research center, The Netherlands Organization (TNO), as reported by van Koten (1967)

In the United States, research led by George Goble at Case Institute of Technology (now Case Western Reserve University) in the 1960's led to the development of the Case-Goble method for driven pile analysis (Goble, 1967, 1975), and the more complex capacity prediction method that is now known as the CAPWAP (<u>CA</u>se <u>P</u>ile <u>W</u>ave <u>A</u>nalysis <u>P</u>rogram) method (Rausche, 1972).

Because they were performed using a pile-driving hammer, both the Case and the TNO methods were known generically as high-strain dynamic load tests, and, until the early 1980s, they were used only on driven piles. Major advantages of the methods, however, were the relatively low cost and high speed of application, which made testing of production shafts economically viable. Dynamic load testing also contributed greatly to understanding of the complex and opposite phenomena of soil set-up, which increased the frictional resistance of a shaft after driving, and soil relaxation, which decreased resistance, as the effects of soil disturbance caused by pile-driving dissipated.

Several researchers had pondered the application of high-strain dynamic testing (HSDT) to drilled shafts and augered, cast-in-place (ACIP) piles, but found the methods uneconomical because of the need to modify or build up the head of the test shaft to withstand the high stresses generated by the impact of the driving hammer, a feature that was necessarily built-in to piles destined to be installed by driving. The potential benefits of HSDT, however, were attractive enough to motivate some of the best researchers in the world, and by the late 1980s, four distinct and viable methods had been developed in Canada, France, Holland, and the United States, that eliminated the need for a specially reinforced shaft head.

These methods have been amply described in the literature, so there is no need for great detail here, but the essence of each method is given to place their contributions in context. Teams from Canada and Holland collaborated on the development of the Statnamic method, in which a reaction mass is placed on or against the head of the shaft. A charge of propellant fuel generates thrust between the shaft and the reaction mass. The method can be employed axially or laterally, and the stresses are controlled by selecting the quantity and combustion rate of the propellant (Kusakabe et al., 2000)

A Dutch team developed the Fundex method, which utilizes a drop-mass system similar to the original gravity driving hammers, but which controls the impact stresses with an array of springs acting between the base of the hammer and an anvil placed on the head of the shaft (Presten and Kasali, 2002)

The French national construction research center (CEBTP), developed SIMBAT, a version of the drop-mass system that utilizes varying and gradually increasing drop height to limit the stresses generated in the head of the shaft, and extrapolates the data to higher loads by numerical modeling (Baker et al, 1993)

The American team developed the 'Apple' drop mass system, named after Sir Isaac Newton's reported inspiration. The Apple system utilizes instrumentation to monitor the drop-mass and the shaft head and so measure stresses and motion. The energy of the impact is controlled by varying the mass of the impactor, and/or the drop height (GRL, 2000)

Regardless of which method was selected, the overall contribution was similar – when combined with information from the construction inspector, and integrity testing results, the data gave geotechnical engineers a better understanding of the factors governing the quality of production shafts, and their effect on the capacity of the foundation.

INTEGRITY TESTING METHODS

Nondestructive integrity testing of deep foundations has been a practical technology in some parts of the world since the early 1960's, and so much has been written about the methods since then that young engineers entering the deep foundations industry today tend to treat them as something to be taken for granted. In reality, however, their acceptance by industry and, particularly, by state agencies in the United States did not become widespread until the late 1990's and early 21st century. Their acceptance is due, in very large part, to the visionary attitude of key experts in deep foundation design and analysis. As far as the United States is concerned, probably the document that most influenced the acceptance of nondestructive test (NDT) methods was the report "Drilled Shafts for Bridge Foundations", published by the Federal Highway Administration (FHWA) in 1993, and made freely available to all state departments of transportation (Baker et al, 1993). The authors of that report supervised the construction of several sets of drilled shafts with deliberate but undisclosed anomalies in them, and invited any interested practitioner of NDT to test the shafts with their preferred method(s) and report their interpretations. The test results were collated and graded in the FHWA report.

The authors of the FHWA report concluded that crosshole sonic logging (CSL) was the most reliable method for detecting anomalies in drilled shafts, and decided that the Impulse Echo and Impulse Response methods were only capable of detecting anomalies that affected more than about 40% of the shaft cross-section. However, it must be noted that the report was based on work performed in 1989, and some of the very few practitioners of NDT for deep foundations at that time had limited experience with the methods. Since then NDT techniques evolved rapidly as the practitioners gained experience, and took advantage of increases in computing power and miniaturization of electronics, which allowed the creation of more powerful and portable testing systems. A similar program of deliberate anomaly creation and blind testing was run at the University of Massachusetts National Geotechnical Experiment Site (NGES) site in Amherst, MA, in 2000, with several of the same participants, together with several new entrants to the practice. The Amherst report indicated a significant improvement in the accuracy of all tests, including Impulse Echo and Impulse Response (Iskander et al, 2001).

In addition to the FHWA and Amherst reports, the NDT methods currently available for integrity testing of new foundations, and for assessment of existing deep foundations that are being considered for re-use, have been well publicized in the technical literature, so this paper refers to them only by name or brief description. The reader who requires more detailed descriptions is referred to American Concrete Institute Report No.228.2R (ACI, 1999) or the book "Nondestructive Testing of Deep Foundations" (Hertlein and Davis, 2006).

Although this paper advocates the use of NDT methods in programs designed to assess deep foundations, it must be stressed that it is very rarely appropriate to use NDT methods as stand-alone techniques for deep foundation acceptance or evaluation programs. In most cases, some additional exploration or testing is necessary to obtain or validate all of the information that is required by the engineer, as the following case histories show.

CASE HISTORIES

FOUNDATION FAILURE AND REMEDIATION – LESSONS LEARNED

One of the most significant events in the evolution of deep foundation quality control was the failure of an eight-foot diameter drilled shaft during the early stages of construction of the John Hancock Tower, in Chicago, Illinois. Excessive settlement of the steelwork above grade caused such concern that work on the project was halted until the cause was identified. An investigation led by Clyde N. Baker, Jr., discovered a 14-foot long void in the caisson. Removal of a temporary casing was believed to be the cause. The problem was remedied, and the project was successfully completed, to give Chicago one of its first iconic high-rise buildings (Baker and Khan, 1971). As a result of the failure investigation and successful remediation, Chicago city engineers began encouraging the use of permanent casing on drilled shafts.

This event also illuminated the benefits of continuous monitoring of key structural and geotechnical parameters during construction, such as structural settlement, foundation loads, vertical and horizontal soil movement and ground water table elevation. Such monitoring programs are now standard practice on most major construction projects, and are mandated by some city building codes. Current technology is able to provide real-time data streaming and instant notification of a monitor data stream that moves outside acceptable limits.

FREE-FALL CONCRETE PLACEMENT

A sometimes contentious deep foundation construction process is the placement of concrete by free-fall, or 'back-chuting' direct from the ready-mix truck. Many engineers still believe that if concrete is allowed to simply fall into place from a height of more than a few feet, it is likely to segregate because the momentum of the heavier coarse aggregate will cause it to 'punch through' the sand/cement matrix and gather at the bottom. Some also argue that concrete striking the reinforcing steel cage will also be more likely to segregate at a result of the impact, and may damage the cage.

A research program, funded by the Association of Drilled Shaft Contractors (now known as the International Association of Foundation Drilling, or ADSC-IAFD), was performed on a site in Northbrook, Illinois, where four 900 mm (36-inch) diameter drilled shafts were constructed in a square group, to a depth of 60 feet. Partial-depth corrugated steel liners were placed in the excavations, and access tubes were installed for CSL testing. Concrete was placed by free-fall, using a variety of common practices, including directing the concrete with a tapered hopper, or ‘elephant trunk’, and guiding it with a shovel placed against the end of the ready-mix truck chute. In at least one shaft, the concrete was placed as poorly as possible, creating the scenarios commonly cited by the opponents of free-fall placement. The shafts were subsequently investigated by CSL and Impulse Response testing, core-drilling, and by drilling a large diameter access shaft down through the center of the group, to allow personnel to access the full depth of each shaft. Windows were cut in the corrugated casings to allow visual review and sampling of the concrete inside.

The research report concluded that the results of this program, coupled with core sampling data from deeper shafts placed by free-fall on projects in the City of Chicago, showed that appropriately proportioned concrete could be placed by free-fall to depths of at least 120 feet in appropriately sized shafts without risk of significant ill effects (STS, 1994).

RE-USE OF EXISTING FOUNDATIONS

In an era when sustainability has become a watchword in construction, the reuse of existing large foundations when redeveloping a previously-used site makes a great deal of economic and environmental sense. A new high-rise building was being planned in Chicago, Illinois, on the site of a former 10-story structure. Dozens of hand-dug caisson foundations with diameters ranging from about 2.0 to 2.5 m (6 to 8 feet) remained from the previous structure. As the site was cleared, it became evident that many of the existing shafts conflicted with the planned locations of foundations for the new structure.

Chicago soils at the project location have two different bearing strata, the glacial hardpan and the deeper limestone bedrock. The difference in bearing capacity of these to strata made it necessary to know the shaft lengths accurately in order to determine which stratum they were founded on, and estimate their capacity. Full depth cores were taken from two of the shafts, both to confirm length and to allow laboratory analysis of the concrete strength. The laboratory tests included measurement of ultrasonic pulse velocity (UPV). Impulse response tests were then performed on all the shafts that were exposed. Shaft depth was calculated from the impulse response data, using a stress wave velocity derived from the UPV measured in the laboratory. The data from these laboratory and field tests were combined with data from an extensive in-house database of local soil-borings, pressure-meter tests and load test results in the same general soil conditions. This information was used by the engineers to assess the capacity of the existing shafts, and incorporate them into the design of the new foundation system.

As a result of this program, a total of 26 shafts were re-used. The estimated economic savings generated were more than $570,000. The reduction in the carbon footprint of the project is harder to calculate, but approximately 2,500 cubic yards of soil did not need to be drilled and trucked out of the city, and about 2,500 cubic yards of concrete did not need to be mixed and hauled to the site.

PREDICTION OF SETTLEMENT IN HIGHLY VARIABLE GEOLOGIC CONDITIONS

Construction of the Petronas Twin Towers in Malaysia presented engineers with a number of challenges that pushed the boundaries of current practice. Apart from the 88-story (452m) height of the towers themselves, a key design feature was a bridge that linked the towers near mid-height, joining both the 41st and 42nd floors. Thus, in addition to the usual concern about foundation settlement, differential settlement between the two towers would also have to be very closely controlled (<13mm across the base of the towers was the goal!).

Investigation of the geology at the site revealed 20 m of alluvium overlying variable thickness strata of residual soils, weathered from sandstone, siltstone, shale, and philite. Beneath this was the Kuala Lumpur limestone, which varied significantly in elevation, and contained a variety of solution features. A number of foundation options were considered, but site conditions and economics finally determined that friction barrettes would be the most cost-effective solution to the settlement control requirement. More than 200 soil borings, 200 cavity-location probes and 260 in-situ Pressuremeter tests were backed up by two fully instrumented 3,500-ton pile load tests to provide data for the final design, which included soil improvement by fluid grouting of cavities and compaction grouting in selected zones

Construction of the foundations was closely monitored using the inspection techniques discussed in the foregoing, plus a program of non-destructive testing using the cross-hole sonic log method to verify the as-built condition of the barrettes. Predicted foundation settlement was 73 mm, with less than 12 mm across the tower foundation mats. Measurement during construction of the towers superstructure showed actual settlement values to be about half the predicted values (Baker, 2006).

CONCLUSIONS

Quality management of deep foundation construction today begins with the observational method, supported by a judicious mix of geotechnical exploration techniques, effective construction inspection and quality control, appropriate integrity testing techniques, practical load-testing methods, post-construction monitoring, and engineering judgment. Its effectiveness is amply illustrated by the changes that have been made to the Chicago Building Codes (CBC) in the last 50 years or so. Ralph Peck once described Chicago as the longest-lived soils laboratory in the country. An article in Engineering News Record (ENR, 2008) confirms Peck's statement by summarizing the significant changes to the CBC that have resulted from the evolution and consistent application of the observational method:

- Allowable bearing pressure on the Chicago hardpan increased from 12 ksf to 60 ksf.
- Allowable bearing pressure for shafts founded on top of rock was not originally addressed by the CBC, but is, at the time of writing, 90 tsf.
- Allowable bearing pressure for rock-socketed shafts increased from 200 tsf to 300 tsf.

The savings created by these code changes extend beyond the economic costs of the project by substantially reducing the environmental impact and carbon footprint that results from deep foundation excavation, spoil transportation, and concrete manufacturing and delivery.

The combined effect of the observational method and improvements in deep foundation construction quality management programs across the United States varies according to local preferences, customs and codes, but the benefits are widespread and well documented. Proactive contractors have used the information generated by these programs to improve construction methods and equipment. Engineers have used them to improve foundation efficiency by optimizing design and constructability, and major agencies such as State Departments of Transportation and Railroad companies have begun to make wider use of foundation construction techniques previously considered problematic, such as drilled shafts and augered, cast-in-place piles, particularly in areas with cohesionless soils, or high groundwater tables.

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