FACTORS AFFECTING CSL DATA QUALITY

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ABSTRACT

Drilled shafts have become very popular deep foundation supports. Drilled shafts can be constructed in a wider range of ground conditions with less noise and vibration than driven piles. Quality assurance (QA) and quality control (QC) of drilled shafts has become a concern due to difficulties in locating defects and determining load bearing capacity. Various non-destructive evaluation (NDE) techniques have been developed to estimate the integrity of the concrete. While NDE techniques provide a powerful tool and have been widely accepted, many variables and unknowns can effect the measurement results. Results are more difficult to interpret, leading to unnecessary litigation over shaft integrity. In addition, influences of surrounding ground, stress states under different load conditions, and crack development during concrete curing further complicate determination of shaft performance.

This study focuses on the load bearing capacity evaluation of drilled shafts under various conditions by analysis methods and numerical models. The analysis is approached first from identification of design criterion and construction procedures, with a brief review of NDE techniques. The analysis method is based on principles and theorems from engineering mechanics, geotechnical engineering, concrete chemistry, and geophysical engineering. The analysis results are used as input to the numerical analysis. The numerical analysis techniques employed in this research are incorporated into the Geostructural Analysis Package (GAP), combining the widely accepted numerical methods of Discrete Element Method (DEM), Particle Flow Method (PFM), Material Point Method (MPM), and Finite Differencing (FD), together with engineering mechanics constitutive models, concrete chemistry models, thermodynamics models, and geophysical tomography and holography for geotechnical engineering application. GAP has been successfully used for ground characterization in highway engineering and mining operations.

This study explores many concerns recently raised for drilled shaft design, construction and maintenance. Recommendations and conclusions may provide engineers with more information and a better understanding of drilled shaft foundations to revolutionize foundation design, concrete mix design, construction techniques, NDE measurement, and defect evaluation, to improve performance and efficiency with reduced litigation risk.

Introduction

The implementation of drilled shafts as deep foundations for bridges has increased dramatically in recent years. A reason for this growth has been the advent of routine non-destructive evaluation (NDE) techniques. Drilled shaft performance, the ability to resist applied loads with an assumed safety factor, is not only dependent on the design but also on the quality of construction practices. All foundation elements must therefore be installed according to the design specifications without flaws. The use of outdated “routine practice” construction specifications and methods frequently produced undesirable situations during construction. Detailed routine inspection procedures by qualified inspectors during drilled shaft construction are essential but may not be adequate in evaluating the final shaft integrity. Construction defects occurring during concrete placement in deep foundations are typically not obvious, and often result in structural stability or safety issues.

Defects are defined as zones in which the drilled shaft structural material or configuration has a lower load carrying capacity than originally designed. Defects in drilled shafts may be caused during drilling, construction, or casing, and may include soil intrusions, honeycombs, voids, and concrete mixed with soil or slurry. These anomalies or defects may produce other long-term weaknesses within the drilled shaft, such as exposing rebar to corrosion. Exposed rebar has reduced resistance to buckling or lateral loads, and thus reduces the life expectancy of the foundation. Current structural design methods for drilled shafts are inadequate because the presence of flaws is not considered. A substantial cost savings can be realized if foundation flaws are detected early, when repairs can be made.

Obtaining accurate and timely information on the integrity of concrete structures such as drilled shaft foundations is essential for project economy, progress, and success. In the mid 1980's, a campaign was launched intending to simulate the development of mobile, inexpensive, reliable non-destructive methods for assessing the quality of drilled shafts during construction (Litke, 2005). These NDE methods are increasingly being adopted for quality assurance on highway projects to assess the integrity of deep foundations and other civil engineering structures. Quality assurance and control for bridge foundations is essential for building a safe and long lasting bridge.

Present NDE methods do not yield absolute values of material physical properties, but measure geophysical dynamic properties that correlate to the material physical properties. Therefore, material modulus and strength within a structure can only be estimated based on the value of in situ geophysical measurements, creating justifiable concern about the accuracy of the results.

Cross-hole sonic logging (CSL), the most popular NDE method within state department of transportations, has been routinely used for several decades to characterize the integrity of drilled shafts. Although 3-D tomographic data acquisition and analysis has been recently applied, CSL technique is still hampered by uncertainty with respect to what specifically constitutes defective concrete.

One fundamental problem is establishing an appropriate technical definition for what may be called "local average velocity (LAV)", which is used as the reference datum within a velocity log along the drilled shaft. The following general guidelines are presently used for rating concrete quality within deep foundations using velocity data from CSL results:

Good/Acceptable concrete:	0-10% reduction (from "LAV")
Questionable concrete:	10-20% reduction
Poor/Not Acceptable concrete:	>20% reduction

Obviously, from the above criteria, it is critical to calculate the "local average velocity" for each drilled shaft with some accuracy. Velocity deviations from the local average at any point along the drilled shaft are used as the measure to characterize the foundation integrity. If a drilled shaft contains several contaminated low velocity zones, the "local average velocity" is proportionally reduced, and therefore invalid concrete ratings may be produced.

Ultimately the question to be answered is not whether the foundation has defects (because defects or flaws are often unavoidable), but to determine the effects of defect frequency, geometry, and location on the structural performance of the drilled shaft foundation.

Purpose and Objectives

This paper will mainly focus on the evaluation of the structural integrity of drilled shafts using the crosshole-sonic logging method. The objectives are to analyze the effectiveness of crosshole sonic logging (CSL) surveys to characterize the integrity and bearing capacity of deep-drilled shaft foundations. Numerical analysis will be employed to isolate, control, and measure the effects of various phenomena.

A well-established, comprehensive numerical model based on the Particle Flow Code (PFC) method is utilized in this study. PFC is a Discrete Element Method (DEM) that uses combinations of small spherical elements bounded by springs of various stiffness to model the larger, more complex elements commonly used in DEM. This modeling method was selected because it supports solids, with effects of friction, interlocking, collisions, and cracking, as well as fluids and solid/fluid interaction. This method also has the capability to model dynamic crack propagation, seismic waves, and static loading in concrete, soil, and other geotechnical materials. The PFC method was also expanded to model a wider range of phenomena, such as concrete curing, heat transfer, thermal cracking, honeycombing, surrounding ground conditions, ground water effects, and corrosion.

This study will simulate CSL surveys under various conditions commonly encountered in the field. The effect of the following factors on velocity propagation will be examined:

1. Access tube-- including tube bending, sensor drift and orientation within the tubes, steel vs. PVC tubes, thermal expansion during concrete hydration, and tube debonding.
2. Rebar--including CSL signal reflection and dispersion, rebar thermal expansion, and rebar debonding.
3. Concrete hydration in typical ground conditions and at different curing times, using chemical hydration rates, heat transfer, and thermal stress.
4. Common defects will be introduced into the models, such as honeycombing, soil intrusion, and thermal cracking. Simulated CSL surveys will be evaluated for effectiveness to detect and classify these defects using simulated waveform analysis.

Next, numerical stress analysis will be performed on defects within the drilled shaft to estimate effects on bearing capacity and structural integrity.

The purpose of this study is to explore the potential to process full-waveform seismic data collected from existing survey techniques to obtain a more accurate and comprehensive estimate of long term drilled shaft performance and structural integrity.

Geostructural Analysis Package (GAP) Model Description

The numerical analysis studies performed in the remainder of this study use the Geostructural Analysis Package (GAP). This method combines well-developed techniques from Distinct Element Method (DEM), Particle Flow Code (PFC), Material Point Method (MPM), and Finite Difference (FD) methods, resulting in efficient simulation of high-resolution dynamic analysis.

The Importance of Thermal Modeling in Concrete Structural Design and NDE

Thermal modeling of concrete elements is important to evaluate the soundness and integrity of drilled shafts. Controlling thermal development, through careful modeling, is a key aspect to understand concrete curing and to minimize the risk of thermal cracking. Construction of large diameter drilled shafts requires a thorough understanding of temperature development during concrete curing. Numerical analysis is useful, not only to provide answers to specific problems, but also to develop a fundamental understanding of interactions between the physical, mechanical, and chemical properties during the curing process.

Thermal modeling is also important for understanding and evaluating CSL data since temperature profiles have direct influence on velocities, and can result in CSL velocity variations. Understanding the temperature history of a structure plays a key role in determining the ultimate integrity of the drilled shaft. The likelihood that velocity variations may be caused by thermal cracking and other temperature related defects in the structure is an important factor to consider when evaluating the CSL profile. Techniques to analyze CSL data for cracking could result in a significant improvement in determining shaft integrity.

Figure 1 shows the result of a numerical analysis of concrete curing after five days. The overall internal stress in the shaft surrounded by rock is nearly zero, but with pockets under high tension and compression. The high tension at the perimeter of the shaft is of concern, because of a higher future cracking potential that could weaken the shaft and expose the rebar to corrosives. The surrounding rock is unaffected, but the clay has deconsolidated to greater than one radius away from the shaft. This is a serious concern, because soil near the surface contributes significant support to the foundation. Reduction in the consolidation of the surrounding ground due to excavation and concrete shrinkage can lower the shaft capacity .

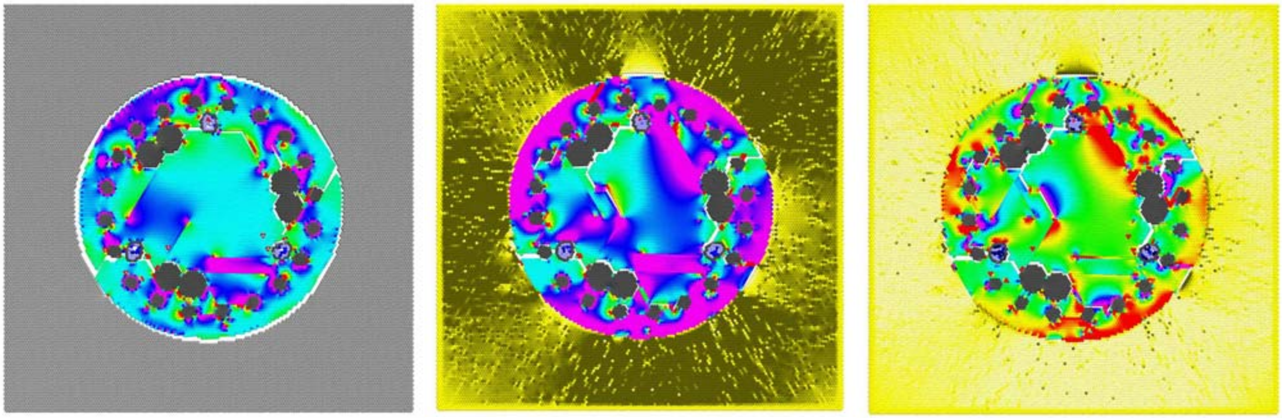

Figure 1 Curing compression of shaft cross-section after 5 days.
Left: Rock. Middle: Clay. Right: Difference

The internal stresses in the shaft surrounded by clay are more pronounced, especially in tension. These stresses will persist in the shaft, unless disrupted by additional cracking. Regions under tension are most likely to crack under future loading. Although both cases have similar fracture extent, the shaft surrounded by clay is much weaker, due to trapped pockets of internal tension.

Factors Affecting CSL Velocity Measurements

Typically, the wave velocity of concrete in a drilled shaft is estimated from the first arrival time obtained during CSL measurements, using the separation distance between the source and receiver tubes at the top of the shaft, assuming the tubes remain vertical throughout the shaft. The first arrival time may correspond to the point at which the signal amplitude first fluctuates, or at the first peak or trough identifiable in the waveform. Uncertainties in source and receiver locations and variations in the definition of the first arrival must be taken into account when interpreting CLS data. Very small changes in source/receiver separation distance and arrival picks can result in large velocity variations. Without proper tube bending measurements, sensor alignment, or proper waveform analysis for first arrival determination, CSL data should be used as a relative guide rather than an absolute value.

Tube locations below the top of the shaft are unknown and are typically assumed parallel. The tube distances at the top of the shaft are occasionally adjusted during the CSL data analysis to obtain a tube separation resulting in more “reasonable” velocities. Tube bending near the top of the shaft is common and often used to justify the practice of adjusting arrival picks in this fashion. This practice can introduce apparent velocity variations in good concrete, or remove velocity variations in defective concrete.

Plots of the signal energy versus depth are often generated in CSL surveys, in addition to plots of first arrival picks. The definition of signal energy often varies from system to system. The signal energy may be determined by summing up the absolute values of a set number of signal samples after the first arrival time, or may be measured from the first major peak after the first arrival, or from the maximum signal amplitude. The energy and velocity plots versus depth are generally used together to indicate regions of compromised concrete quality. Some CSL data collection systems do not attempt to analyze the signal data, but simply plot the waveforms with depth for visual inspection.

CSL velocity variations may indicate zones of lower quality concrete, voids, and honeycombs in a drilled shaft. Actual defects are difficult to detect using CSL data in its present form, because CSL measurements must be assumed accurate and absolute, not approximate, relative, and massaged. When good CSL data is available and reconstructed variations can be trusted as defects, the influence of a defect on foundation performance should be carefully examined. Design loads and the load bearing assessment should be taken into consideration relative to the anomaly location within the drilled shaft. For example, an anomaly near the base of a friction shaft may not significantly affect the load carrying capacity. The same anomaly in an end-bearing shaft in very loose soil may be of greater concern, depending on how the loads are applied to the shaft and transferred to the surrounding soil. An end bearing shaft experiences friction with the surrounding ground, as does a friction shaft. Actual loading conditions and load distribution should be evaluated to determine the effect of anomalies on overall shaft performance for defect definition. A drilled shaft should not be rejected simply because CSL surveys suggest lower concrete quality in certain zones, or accepted based on consistent CSL results.

CSL is not restricted by shaft length and can detect multiple anomalies within a drilled shaft, with accurate data collection. Combined with tomography and the option to create more signals on angled or offset paths, the size and location of defects can be better estimated. However, CSL is relatively expensive and requires pre-installation of access tubes. Debonding between tubes and concrete can seriously affect the results, corrupting measurements of entire sections of the shaft. Variations in hydration rates during concrete curing can also create anomalies in first arrival times and signal energies, falsely indicating lower quality concrete.

If only first arrival times or signal energy levels are used, no information outside the rebar cage can be obtained from CSL tests. Placing the access tubes outside the reinforcing cage significantly reduces the quality of data and complicates interpretation. Signals attenuate due to thermal cracking and debonding of the concrete in regions adjacent to the rebar cage. In friction shafts, concrete integrity outside the steel-reinforcement cage is more critical to assess than the core of the shaft. This is a serious limitation of the CSL test.

CSL Velocity Variations

Actual variations in sonic velocity within concrete structures such as drilled shafts originate from two sources, “structural” and “chemical”. This division breaks down naturally from the basic nature of concrete structures. Fundamentally concrete structures can be conceptualized as a form of artificial stone, formed from constituent components as a result of a clearly defined chemical process - the hydration of the cement. Water chemically reacts with the cement. Cement does not dry out, and water does not escape into surrounding porous materials or evaporate into the air, as is commonly thought. Defects resulting in a substantial reduction in the strength of concrete structures from its designed capacity may have two origins. Structural defects can be the result of a physical deviation in the process of forming the concrete structure, since structural design assumes a uniform mass of well mixed concrete. Defects may also occur when the concrete mixture is placed in the desired form as intended. These defects come from inherent weakness and variability in the process of the concrete curing itself. From the time concrete is poured to the time it is fully set, many dynamic processes take place. Variations in chemical reactions that form the concrete can result in decreased design strength. A defect in the concrete that decreases the performance of the shaft can be classified as a structural defect.

The numerical analysis shown in Figure 2 shows that the stress in the drilled shaft is not uniformly distributed through out the depth of the shaft. Soil density, friction angles of geo-materials, defects in the shaft, and consolidation levels are the major control factors for stress concentration. In these stress concentration zones, local stresses may exceed the strength of the material to cause local failure within the material. In these stress concentration zones, materials may also experience large plastic deformations, which aggravate the propagation of cracks and worsen the corrosion process.

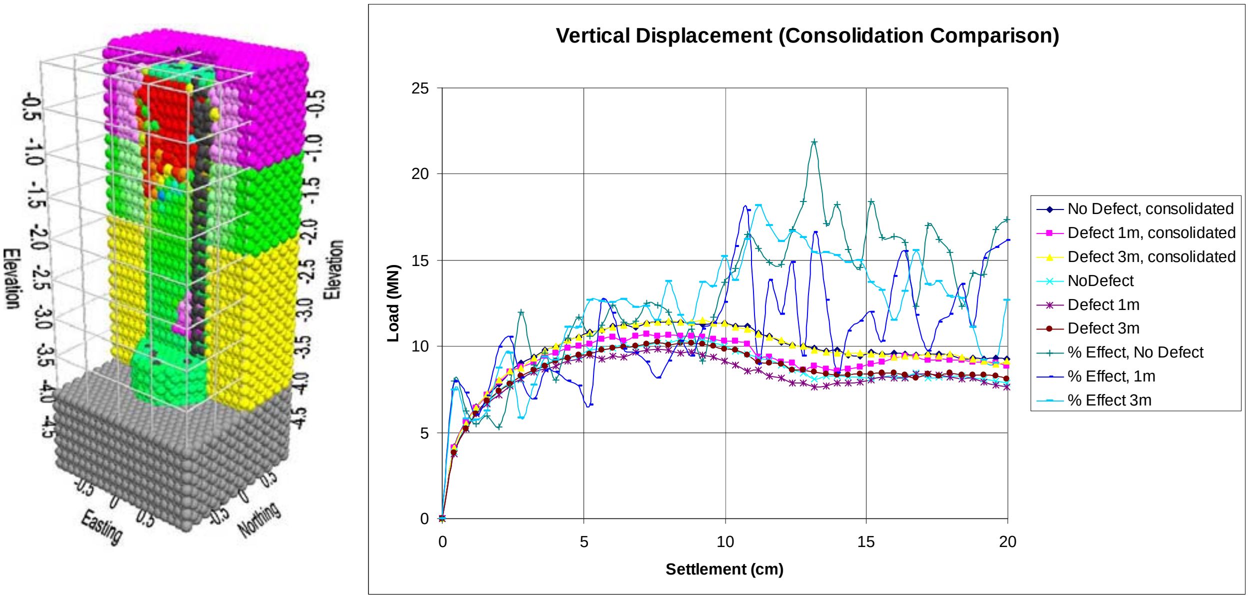

Figure 2. Effect of Soil Consolidation and Shaft Defects on Load Capacity

Conclusions

Several conclusions may be explicitly or implicitly inferred from this study. This study suggests that current techniques for generating CSL data plots of velocity and energy are unreliable for detecting cracking and estimating strength. CSL plots of velocity and energy are to some degree reliable for estimating concrete consistency, as CSL data processing techniques have potential to detect large voids and honeycomb regions.

Current methods employed for first arrival determination are arbitrary and open to manipulation. Manipulation of arrival picks can result in velocity artifacts, or can eliminate existing defects. Lack of tolerances in CSL data collection equipment is also a problem, which may result in arrival pick variations. Poor quality CSL data collection equipment results in poor quality, noisy, and unreliable data. Failure to account for tube bending results in velocity artifacts. Failure to account for sensor position and orientation in access tubes can result in velocity artifacts. Thermal expansion of access tubes results in tube de-bonding in the upper portions of the shaft, further complicating data interpretation. Access tubes transport heat from the shaft, and can result in concrete cracking.

Concrete cures as a result of chemical hydration processes, and does not dry by loss of moisture. Surrounding ground conditions affect curing rates and temperature gradients. Temperature gradients above a certain level result in cracking. Stress in the drilled shaft is not uniformly distributed through out the depth of the shaft. Soil density, friction angles of geo-materials, defects in the shaft, and consolidation levels are the major control factors for stress concentration. Failure to account for variations in curing rates, shaft temperatures, heat transfer, stress, cracking, and the surrounding environment will likely result in velocity artifacts.

Quantitative processing techniques, such as tomography, should not be used on CSL data that has not been quantitatively acquired or processed. With quantitative data collection, numerical inversion and analysis has potential to improve data processing and interpretation for CSL, providing objective, automated techniques for evaluating the data. This includes in situ measurement of concrete properties, shaft evaluation outside of the reinforcement cage, shaft cohesion with the surrounding ground, shaft bulging or necking, and cracking defects. Numerical analysis has the potential to evaluate effects of shaft defects and estimate load capacity, and account for variations in curing rates and estimate cracking. Numerical analysis may also have application to long term effects, such as corrosion and scouring, with further study.

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