SONAR CALIPERING OF SLURRY CONSTRUCTED BORED PILES AND THE IMPACT OF PILE SHAPE ON MEASURED CAPACITY

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ABSTRACT
Sonar callipering technology is increasingly being used to reveal the shape of bored pile excavations in wet conditions. Case studies and numerical analyses using the software program FLAC illustrate the role of the sonar calliper in evaluating capacity of piles with anomalous shapes. The FLAC numerical model is calibrated to the results from a sonar-callipered test pile with enlarged cross-sectional areas, which was also load tested using the Osterberg cell method. The model is then used to predict the response of a uniform pile to the same load test, illustrating the importance of accurate measurement of pile shape in the developing recommendations for production piles. The model is also used to compare the equivalent top load curve calculated from the Osterberg Cell test with the curve resulting from a model of a top load test and to illustrate the impact of stress concentrations in load tests.

RÉSUMÉ
La technologie du calliper accoustique (SONAR) est de plus en plus repandue afin de reveller la forme des excavations pour pieux fores en conditions humides. Certaines etudes de cas ainsi que l'analyse numerique utilisant le logiciel FLAC demontrent l'avantage du calliper acoustique dans l'evaluation de la capacite des pieux de formes anormales. Le model numerique FLAC est calibre contre les resultats provenant d'un essai suivi par calliper accoustique sur pieux possedant des aires de surface surdimensionnees ; le test etait aussi charge a l'aide de la methode de la cellule d'Osterberg. Le modele est ensuite utilise pour predire le comportement d'un pieux uniforme soumis au meme essai de chargement, ce qui demontre l'importance de mesurer la forme des pieux avec exactitude durant le developpement de recommendations reliees aux pieux de production. Le model sert aussi a comparer la courbe equivalente de chargement par le haut calculee a partir de l'essai par cellule d'Osterberg envers la courbe generee par un model numerique estimant un essai de chargement par le haut ainsi qu'a illustrer l'impact des concentrations de contraintes dans les essas de chargement.

1 INTRODUCTION

It is theorized that anomalies in the cross-sectional area of a pile increase the resistance to loading, compared to a pile with a uniform diameter. This concept is nowhere more important than when interpreting the results of a pile load test and developing recommendations for the allowable capacity of production piles. While most foundation engineers recognize the importance of static load testing as a backbone of safe and economical design, a load test performed on a bored pile containing shape anomalies can leave the engineer with an unconservatively high estimate of pile capacity.

Typically, inspections of pile excavations are limited to the base and predominantly only in dry excavations. Attention is also paid toward verticality, but concern over pile diameter is generally focused on minimums and not on excursions. As engineers increasingly use slurry stabilized bored piles to reap their increased performance over dry excavations below the water table, the question of shape is often pushed aside and quality control and assurance may suffer.

Recent advancements in sonar technology can routinely determine shaft diameter, volume and verticality in wet conditions; enabling quality control without sacrificing performance. Engineers are becoming more cognizant of the importance of shaft shape in interpreting data from strain gages in pile load tests (Hayes and Simmonds, 2001). But gross anomalies in shape can not only make interpreting instrumentation difficult, but also limit the applicability of load test results to production piles.

We present four case studies herein profiling anomalous pile shape and its impact on quality assurance and pile capacity. A numerical analysis is also performed for one of the case studies to demonstrate the importance of accurate measurement of pile shape.

2 CALIPER TECHNOLOGY

The most common methods for determining the shape data of bored pile excavations made in wet conditions involve the use of either mechanical or sonar callipering devices.

2.1 Mechanical Caliper

A mechanical caliper typically consists of a spring-loaded frame with arms which extend to contact the excavation sidewalls. Displacement transducers are incorporated into the arms so that as the device is raised from the bottom to the top of the excavation, the distance from the tip of the arm to the center of the device can be recorded. Among the limitations of a mechanical device is the difficulty of use in excavations exceeding 1-meter in diameter and the inability to expose the presence of deformations located between the arms. In addition, the mechanical caliper cannot provide verticality measurements or information about shape beyond only average diameter. The contact between the spring-loaded arms of the caliper and the sidewalls also tends to disturb the medium that is being measured, resulting in potentially inaccurate results.

2.2 Sonar Caliper Devices

Sonar callipering devices typically consist of a sonar transceiver (ultrasonic echo sensing system) mounted on a weighted head. As the sonar device is lowered into the excavation, the time required for the signal to travel from head to the sidewall and back is used to determine the distance to the sidewall. For the portion of the excavation that the sonar is deployed, variations in distance between the center of the excavation and the sidewall can be determined. Depending on the power of the transmitter and the density of the drilling fluid, it is not uncommon for sonar callipering devices to accurately profile pile excavations up to 3.9m in diameter

The most basic devices utilize a unidirectional or bidirectional sonar head (a single transceiver or two, horizontally opposed transceivers), allowing measurement of only one or two points along the excavation sidewall at any given depth. The KODEN D-682 is one example of a bi-directional sonar device. If two orthogonal measurements along the axis of the excavation are required, for example to determine verticality, these devices must make a minimum of two or as many as four passes to generate the required data. The use of only two orthogonal measurements can also lead to errors in interpretation when the excavation is not perfectly plumb.

Figure 1 illustrates the potential error associated with this limited data if the direction of divergence in verticality is not coplanar with those of the sonar profiles. The apparent diameter measured in these data sets can be even smaller than the tools used to excavate the pile causing much confusion and eroding confidence in the other measurements indicated by the device.

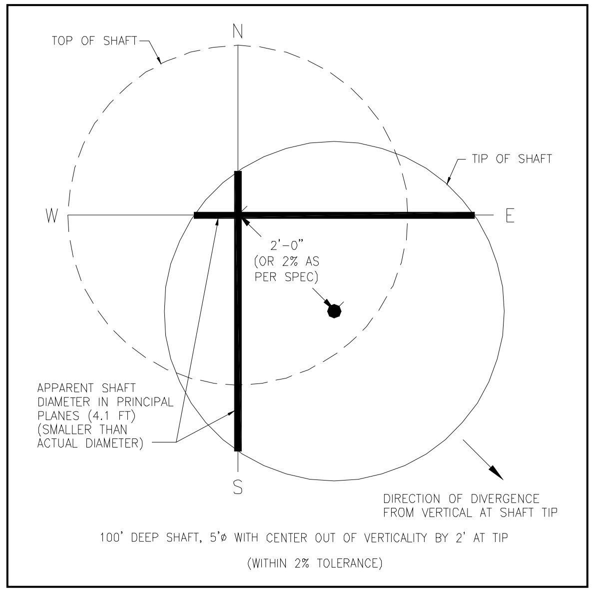

Figure 1. Potential Error in Diameter Arising from "basic" Sonar Caliper Measurements (LOADTEST, Inc.)

Caliper devices containing multi-directional heads can obtain data from at least two planes in each pass. This greatly simplifies the data collection and indicates verticality divergence more clearly. However, a multi-directional head may still miss anomalies present between the transceivers and requires multiple passes and interpolation to even begin to define the shape of the excavation.

Currently, the most advanced sonar caliper we know of contains an omni-directional head. The unit, developed by LOADTEST, Inc. consists of a single transceiver mounted on a 360° rotating head (Figure 2).

Figure 2. 360° Sonicaliper (LOADTEST, Inc.)

The unit is lowered and raised by the signal cable over a guide wheel which is attached to a support frame at the surface of the excavation. The cable maintains the position of the unit along a plumb line throughout the length of the pile, allowing for accurate measurements of verticality, in addition to shape data. Proprietary software is used to calibrate the location of the sonar device within the excavation to measure shaft diameter and head location at all times.

The profile of the excavation is generated by positioning the head at discrete depth intervals and performing a 360° scan, producing a data set at each depth. The data may then be used to generate either a 2-D representation or a 3-D wire frame of the excavation shape, similar to those presented under the case studies herein.

3 CASE STUDIES

As the following cases illustrate, pile shape revealed by advanced sonar caliper measurements is rarely plumb, often not axially symmetric and sometimes extremely anomalous. The cases presented herein were collected from diverse geographical locations for bored pile excavations made under water, mineral and synthetic slurries and using various drilling tools and methods. The presence of anomalies in such a varied sample underscores the importance of investigating pile shape in all locations and whatever the method of excavation.

3.1 Bridge Replacement, Benicia, California

This particular project contains one of the most useful bi-directional callipering profiles that we have encountered. The limitation of the bi-directional head (KODEN DM-682) was, to a small degree, overcome by performing four additional passes in addition to the conventionally accepted two passes. This process yielded continuous profile data for the sidewalls walls at every 30 degrees.

The design for the bored pile at the test location consisted of a nominal 2,200-mm diameter pile socketed approximately 22 meters into siltstone and claystone. A 2,580-mm O.D. permanent steel casing was driven through the top 36 meters of overburden and seated roughly 4 meters into the top of the rock and the socket was excavated using a reverse circulation drill (RCD) rig. Initial caliper results indicated that the shaft verticality exceeded the specified 2% tolerance. In addition to this, numerous irregularities in the shape of the pile were noted resulting from attempts to correct for deviations from verticality. Figure 3 depicts estimates of the shape of the pile at selected locations below the tip of the casing.

The design specified an Osterberg Cell (O-cell) assembly (Osterberg, 1991) to be installed 14 meters below the tip of the casing, with three levels of strain gages between the assembly and the tip of the casing for determination of side shear in the socket. Although the pile construction was well out of tolerance, the contracting authority wisely carried out the load test as planned, to determine the impact of the known irregularities on shaft capacity. Using the caliper data to analyze the test data from the strain gages yielded a different load distribution and a lower unit load transfer in the rock socket than that using the nominal diameters.

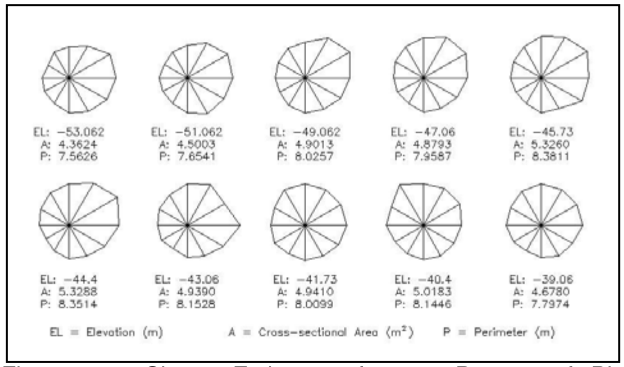

Figure 3. Shape Estimates from 6 Passes of Bi-directional Caliper (LOADTEST, Inc.)

Figure 4 shows that without the shape data, the unit friction values would have been over predicted by 29%.

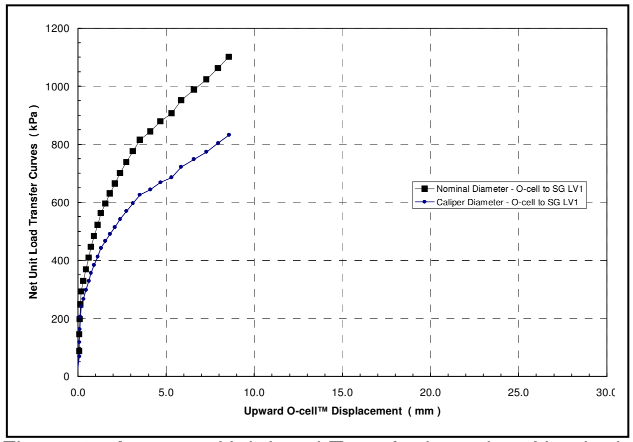

Figure 4. Apparent Unit Load Transfer based on Nominal and Callipered Data (LOADTEST, Inc.)

Due to the irregularity of the pile shape, it would not have been possible to properly analyze the load test data if not for the information produced by the caliper results.

3.2 High-rise Condominium, Panama City, Panama

A full-scale load testing program was underway at the site of a proposed 70-story condominium in Panama City, Panama. One of the load test piles was excavated under natural groundwater seepage, into a hard agglomerate rock to a depth of approximately 20 meters below grade. The excavation was difficult and the contractor spent considerable time using progressively larger rock augers to excavate the required socket length. Once the excavation was ready for installation of the reinforcing cage, it was apparent that the attached O-cell assembly could not be installed beyond approximately 17 meters below grade. A sonar caliper was brought to the site and 360-degree profiles were recorded for the pile excavation between 4.4 meters and 18.3 meters below the ground surface. A plan view of all the caliper profiles is shown in Figure 5.

The hatched area in the figure clearly shows the zone of sidewall encroachment, presumably caused by a "walking" rock auger which was preventing full insertion of the reinforcing cage and loading assembly. The profiles also showed large variations in cross sectional area in the rock and overburden materials. Equivalent diameters for the nominal 1.80-meter diameter pile varied between 1.83 and 2.86 meters over the length of the callipered excavation. The known shape of the pile excavation was used in the analysis of the data from the subsequent load test on the pile.

The apparent unit friction values calculated from strain gages in the rock socket were on the order of 600 kPa at serviceable displacements. These values, calculated using the actual pile shape were nearly 40% less than those values which would have resulted from using the assumed nominal diameter of 1.80 meters. Erroneous unit friction values resulting from uncertainties in pile shape could have had serious implications on the performance of the foundation system designed on those values. The engineer could have easily assigned allowable unit friction values which would not have been attainable from a uniformly shaped production pile.

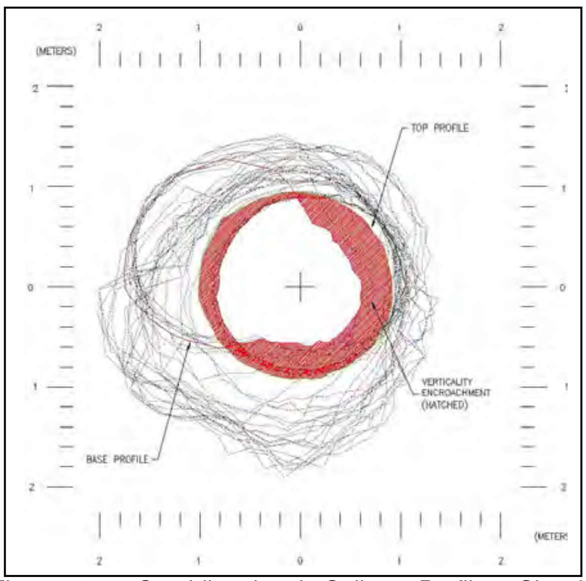

Figure 5. Omnidirectional Caliper Profiles Showing Sidewall Encroachment (hatched) and Highly Irregular Shape (LOADTEST, Inc.)

Once again, knowing the shape of the pile excavation was instrumental in first solving a construction difficulty and more importantly, properly analyzing the results of a load test.

3.3 Bridge Replacement, San Juan, Puerto Rico

During construction of the nominal 1,800-mm diameter test pile for a bridge replacement, the volume of the spoils removed from the excavation appeared to be significantly more than theoretical. In an attempt to evaluate the suitability of the pile for load testing, an omnidirectional sonar caliper survey was performed. Figure 6 shows the 3-D wireframe generated from the caliper profiles.

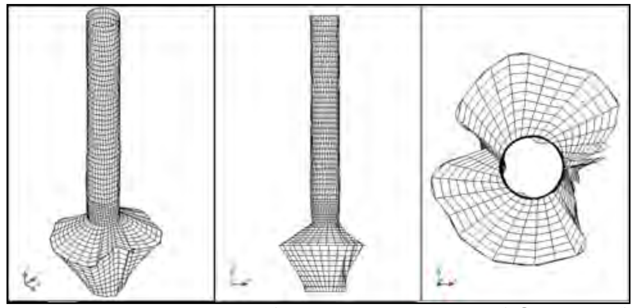

Figure 6. Isometric, Profile and Plan Views of Cave-in of a 1.80 meter Diameter Pile (LOADTEST, Inc.)

The caliper was able to obtain shape data for the first 18.3 meters of depth below the top of the temporary casing. While the majority of the excavation length was temporarily cased, the data from the 4.78-meter uncased portion of the excavation showed a significant cave-in. The enlargement extended to a maximum width of 6,375 mm at its widest point, before necking back down to 2,715 mm at the deepest point we were able to caliper. After reviewing the caliper data on site, the engineer decided to reject the pile and the contractor proceeded to excavate at a new location. The logical question that followed however, was, "What would have happened if we had tested that pile and how would the results of the load test have over-predicted the capacity of a pile that did not contain such a discrete excursion in shape?" The next case study outlines the opportunity we had to investigate just such a situation, and the numerical modeling that attempts to quantify the potentially unconservative result of testing a pile that has an unknown shape.

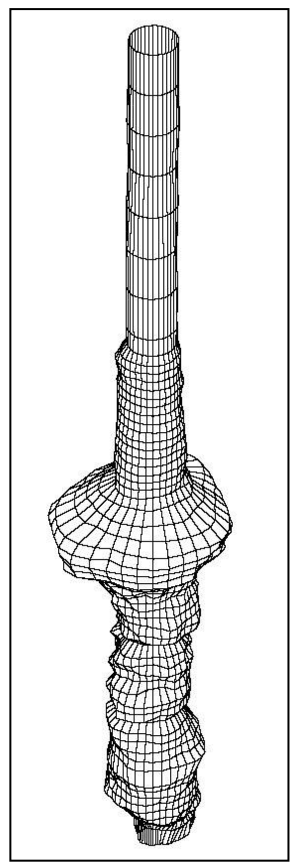

Figure 7. Rendering of Pile Shape (LOADTEST, Inc.)

3.4 Bridge Replacement, Molokai, Hawaii

The load test program for the FHWA emergency replacement of a bridge on Molokai included a full scale static load test on a test pile with a design diameter of 1.20 meters and a depth of 25 meters. In order to eliminate the need for a reaction system, an O-cell test was chosen and an additional 9.3 meters of pile was excavated below the proposed production pile tip elevation to serve as reaction for the O-cell. The pile was founded in an extremely variable stratigraphy consisting of soft to medium dense lagoonal deposits underlain by stiffer alluvial deposits. A steel casing was used to support the top 12.7 meters of the excavation into the soft lagoonal soils. The remainder of the excavation was performed using rotary methods and using polymer slurry to keep the excavation sidewalls from sloughing. During the drilling process it became apparent that a large amount of soil was being excavated without a commensurate increase in excavation depth. As in similar cases, the sonar caliper profile revealed a cave in having a maximum diameter of 4.3 meters approximately 19 meters from the ground surface. Having knowledge of the exact shape of the excavation, the engineer authorized the contractor to continue with construction of the pile and the subsequent load test. While it was assumed that the tested pile would be stronger due to the presence of a 4-meter bulge near its center, and given that the caliper data existed to perform the requisite calculations, it was not possible to estimate by conventional methods exactly how much stronger the pile was than one constructed with a uniform diameter. The following section outlines the numerical modeling performed on the test pile data which attempts to address this unknown.

4 NUMERICAL MODELING DEMONSTRATING THE EFFECT OF IRREGULARITIES IN PILE SHAPE

4.1 Modeling Methodology and Cases Examined

To demonstrate the impact of irregularities in pile shape on response to loading, a series of numerical analyses have been completed using FLAC, a finite difference geomechanical modeling program. The analyses were based on an O-cell test completed on a sonar callipered, cast-in-place concrete test pile for the bridge replacement on the island of Molokai, Hawaii. The results of the sonar calliper on this pile are presented above, and this section focuses on the numerical modeling work. The shape of the pile is very irregular, with a large bulge in the concrete pile within dense gravelly soils above the O-cell.

An axisymetric configuration is utilized to model the single pile and surrounding soil. The Duncan and Chang hyperbolic constitutive model (Duncan et al, 1980) is used to represent the soil materials, and a linear elastic constitutive model is used for the concrete pile. The model does not include simulation of creep.

There is no interface in the model between the pile and the soil: unit skin friction values are not an input for the model. Rather, the concrete of the pile is assumed to be completely bonded to the surrounding soil. This approach is considered the most reasonable representation for a cast-in-place concrete pile because cement is a material specifically intended to bond to soil particles, and irregularities in the shaft enhance this bonding. The stress and displacement response of the pile to loading results from elastic deformation of the concrete pile together with the shear and volumetric deformation of the soil surrounding the pile.

The approach to the numerical modeling was to calibrate the model to the actual O-cell test by varying the parameters of the soil layers around the pile until the model captured the field behavior of the test pile. Additional cases were then modeled using these same soil parameters and varying the geometry of the pile and loading conditions. Specifically, the following cases were modeled:

Case 0i – Model Calibration Using O-cell Test Results for Irregular Shaped Pile:

- A model was developed of the actual O-cell pile load test that included the as-constructed pile shape determined from the sonar caliper.
- In this case, the strength and stiffness parameters of each soil layer were adjusted until the model was in reasonable agreement with the load-displacement data for the top and bottom of the load cell, and also to the load distribution within the pile recorded by strain gages.
- These soil parameters were used for all subsequent modeling cases.

Case Ti – Top Loading Simulation

- Same pile geometry as Case Oi, except the O-cell is removed from the model (replaced with concrete), and the pile is loaded from the top.
- This case allows comparison with the “Equivalent Top Load-Movement Curve” that was calculated from the O-cell test.

Case Ou – Simulated O-cell Test with Uniform Shaft Diameter

- Same as Case Oi, except a uniform shaft diameter is used, with diameter equal to the average diameter from the sonar caliper results. The volume and hence weight of the concrete pile in this case is the same as in Case Oi.
- This case demonstrates the impact of a significant irregularity (e.g. a bulge) in shaft diameter on the O-cell test results by comparison to a uniform pile

Case Tu - Top Loading with Uniform Shaft Diameter

- Same as Case Ou, except the O-cell is removed from the model and the pile is loaded from the top, to examine the predicted response to top loading of a uniform pile for comparison to Case Ti for the irregular pile.

There are some limitations to the modeling and the available data, summarized as follows:

- There was no borehole information available below location of the O-cell, and therefore layers of soil materials had to be assumed below the O-cell
- The sonar caliper was not used for the lower 4 meters of the length of the pile, and therefore an assumed diameter had to be used in the model.
- The model is axisymetric and therefore three-dimensional variations in pile shape that were identified by the sonar caliper are not specifically modeled. For the calibration of the model to the test pile, the average

diameter at each elevation in the pile is used as the diameter for the axisymetric model pile.

- The Duncan and Chang hyperbolic model does not simulate creep behavior (time-dependent deformation at constant stress). Therefore, no effort was made to calibrate the model at loads above the apparent creep limit determined in the O-cell test.
- Initial strain gage readings prior to concrete placement (i.e. zero readings) were not available. Therefore residual, locked-in stresses and loads in the pile resulting from concrete curing (Fellenius, 2002) are not known and therefore not modeled. However, stresses in the pile due to the self-weight of the concrete pile are included in the modeling, as described further below.

4.2 Model Calibration

The geometry of the model for case Oi, including both soil layers and pile geometry is shown in Figure 8. The groundwater table is shallow, at approximately 1 meter depth. It is noted that the bulge in the pile above the O-cell occurred within a dense gravel layer. A softened zone of soil below the pile tip is required for calibration of the model, which is often an observed reality that results from loosening of the soil below the drill bit.

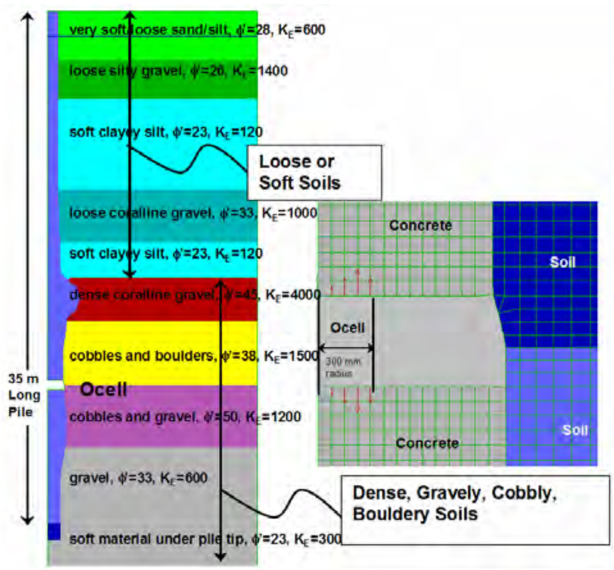

Figure 8. Geometry of Axisymetric Model of O-cell Test on Irregular Shaped Pile

The model is first brought to gravity equilibrium without the concrete pile and using an at-rest earth pressure coefficient, K_o, of 0.5 for all soils. The pile is then inserted into the soil mass and the model is again brought to gravity equilibrium prior to O-cell or top loading. Thus, static loads and stresses due to the self-weight of the pile are incorporated in the model, but this procedure results in zero shear stress in the soil against the shaft of the pile. Shear stresses against the pile resulting from concrete curing (Fellenius, 2002) are not specifically included in the modeling.

To determine the loads in the model at each strain gage location, stresses are recorded in an element of the model at the exact location (both vertical and radial from the pile centerline) as each strain gage in the field test pile. In this way, any stress concentrations that occurred in the field test pile at each strain gage are also captured in the model. Stresses in the model are converted to loads using the pile diameter at the elevation of each strain gage.

The O-cell itself is modeled by inserting a void in the model and applying pressures against the boundaries of the void to balance the previously existing, gravity induced stresses in the model. O-cell loading is then accomplished by applying additional upward and downward pressure to the concrete above and below the O-cell. The pressures representing O-cell loading and top loading are only applied over the diameter of the loading ram (600 mm). In this way, stress concentrations are captured in the model, which result from the fact that the ram diameter for an O-cell or top-load test is typically much smaller than the pile diameter. The O-cell load is applied in stages using pressures that produce 1,800 kN load increments, and the model is brought to static equilibrium after each increment. The hyperbolic parameters that were developed through Case Oi and used in all the modeling are presented in Table 1.

Soil Layer	ρ	ϕ'	K_E	R_F	m
very soft/loose sand/silt	1650	28	600	0.9	0.25
loose silty gravel	1750	26	1400	0.8	0.25
soft clayey Silt	1600	23	120	0.9	1.0
loose coralline gravel	1290	33	1000	0.9	0.25
dense coralline gravel	1340	45	4000	0.7	0.5
cobbles and boulders	2060	38	1500	0.9	0.25
cobbles and gravel	2160	50	1200	0.6	0.25
gravel	2150	33	600	0.9	0.25
soft soil under pile tip	2180	23	300	0.9	0.5

Table 1. Soil Parameters for Numerical Model

Notes: ρ = bulk density (kg/m^3), ϕ'=effective friction angle (º), c'=effective cohesion=20 kPa, ν=Poisson's ratio=0.15, n=shear exponent=0.5 for all soils. See Duncan et. al. (1980) for definitions of the hyperbolic stiffness parameters, K_E, n, R_F and m.

Based on the O-cell test results, the Young's modulus of the concrete is taken to be approximately 25,000 MPa, with a Poisson's Ratio of 0.15.

4.3 Model results

Figure 9 shows load-deflection curves for the top and bottom of the O-cell for the actual O-cell test on the irregular shaped pile, the corresponding model result (Case Oi) and the model result for the uniform pile (Case

Ou). The O-cell load presented on this figure is the load applied in each direction, upward and downward. Figure 9 shows that the model reproduces the load-deflection result from the O-cell test up to the apparent shaft creep limit for both the upward and downward movements of the O-cell. At loads higher than the creep limit, the model reproduces the data for the upward movement of the O-cell accurately up to the point where a 4-hour hold (creep test) commenced. The model over-estimates the downward movement of the bottom of the O-cell at loads higher than the creep limit. The inaccuracy of the model for loads higher than the creep limit is the direct result of the limitation of the model, which does not simulate creep behavior, and predictions from this method of modeling are only considered valid for loads prior to the initiation of significant creep behavior.

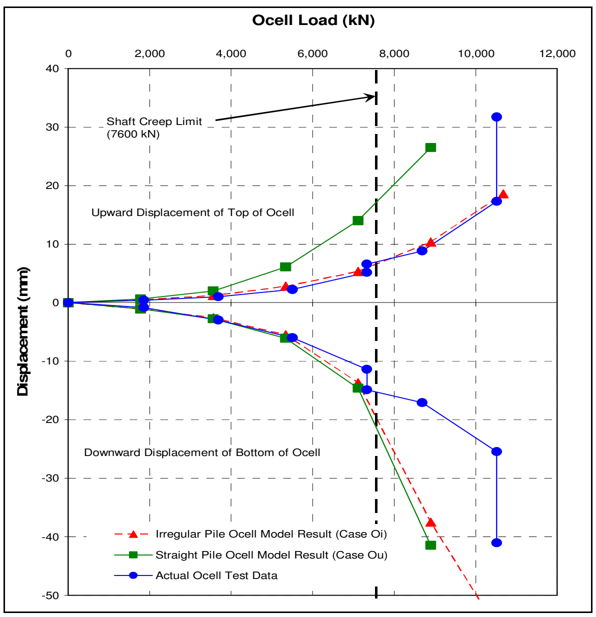

Figure 9. Load-Deflection Curves for the Actual O-cell Test and the Models of the Irregular and Uniform Piles

Figure 9 also clearly shows that when the bulge in the pile above the O-cell is removed and a uniform pile is modeled, the upward movement of the top of the O-cell is more than double that for the model of the irregular pile. The downward movement of the bottom of the O-cell is similar in the irregular and uniform piles, which is reasonable as the shape of the irregular pile below the O-cell is not that different from the shape of the uniform pile. The irregular shape pile is slightly tapered below the O-cell, resulting in slightly less downward movement than for the uniform pile.

The load distribution in the pile (i.e. at the elevation of each strain gage) for the calibrated model (Case Oi) and the actual O-cell test are presented in Figure 10. Calculated loads from the O-cell test at strain gages SG3, SG4 and SG5 are omitted from the figure, because many of these apparent loads were higher than the applied O-cell load, which is an impossibility that is examined through the model results, as follows.

In the model, loads at the strain gage elevations shown on the load-distribution figures have been calculated by taking stresses in each concrete element of the model at the elevation of each strain gage and multiplying by the contributing area for each element. Thus, the plotted model loads are averages across the pile diameter. However, in the actual O-cell test, strain gages were placed at a radial distance from the center of the pile of approximately 450 mm, while the pile radius was considerably larger, ranging from 800 mm to 2200 mm. Therefore the apparent loads at the strain gages are impacted by stress concentrations that result from the relatively small ram diameter in comparison to the pile diameter.

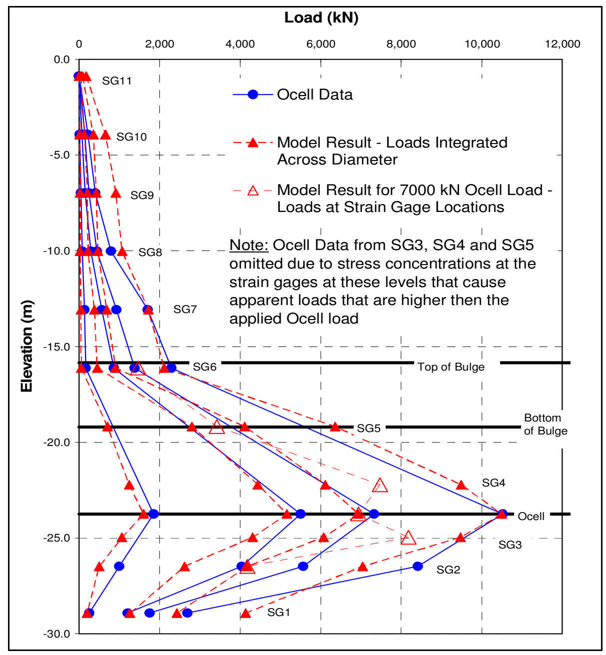

Figure 10. Load Distribution in Pile for the Actual O-cell Test and the Model of the Irregular Shaped Pile

To demonstrate the effect of stress concentration near the loading ram, Figure 10 also includes model results for the 7,000 kN load increment wherein strain gage loads are calculated by taking the stresses in the model elements at the same radial location as in the O-cell test, and multiplying by the total cross-sectional area of the pile – i.e. exactly the same method used to calculate loads from the actual O-cell test. It is clearly seen that this calculation method results in apparent loads that are higher than the applied O-cell load for the strain gages close to the O-cell, exactly as occurred in the actual O-cell test.

The model results suggest that load concentrations near the O-cell could be responsible for the apparent load calculated from strain gages being higher than the applied load. In addition, a zone of lower modulus, or micro-fractured concrete, near the strain gage location may yield the high strains which are falsely implying a load higher than that applied. Figure 11 shows the load distribution in the pile for the calibrated model (Case Oi) and the model of the uniform pile (Case Ou) for selected

O-cell loads. The model results show that the loads above the elevation of the bulge are considerably less for the uniform pile than for the irregular pile. These lesser loads result in greater upward displacement of the top of the O-cell for the uniform pile, as shown in Figure 9.

Figure 11 also includes model results for the 7000 kN increment calculated from the elemental stresses at the same radial distance as the strain gages, as described for Figure 10, that demonstrate that stress concentrations near the O-cell also impact the apparent loads in a test on a straight shaft pile.

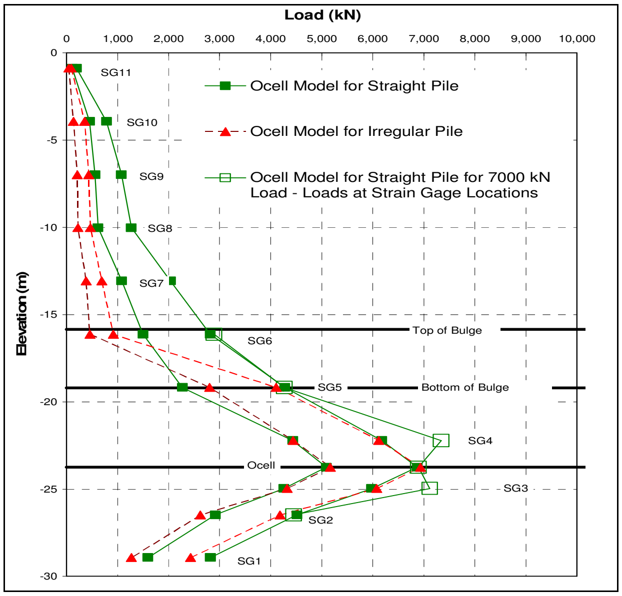

Figure 11. Load Distribution in Pile for the Model of the Irregular and Uniform Piles

The contours of vertical displacement and principal effective stress in the model with 9,000 kN O-cell load are shown in Figure 12. The results shown in Figures 9 through 12 clearly demonstrate that the bulge acts to key or anchor the pile into the surrounding soil. The effects of this anchor are to reduce upward movements compared to a uniform pile and to cause load concentrations in the pile beyond those that result from the presence of dense layers of soil.

Figure 13 shows the results of modeling of top load tests for the irregular shaped pile and the uniform pile, Cases Ti and Tu respectively. The results clearly show the load concentration at the locations of the strain gages above the bulge for the irregular pile, and the smoother load distribution that occurs in the uniform pile. Figure 13 also includes model results for the 21,000 kN increment calculated from the elemental stresses at the same radial distance as the strain gages, as described for Figure 10, that demonstrate that stress concentration near the loading ram affects the apparent load distribution calculation in a top-load test in exactly the same manner as in an O-cell test.

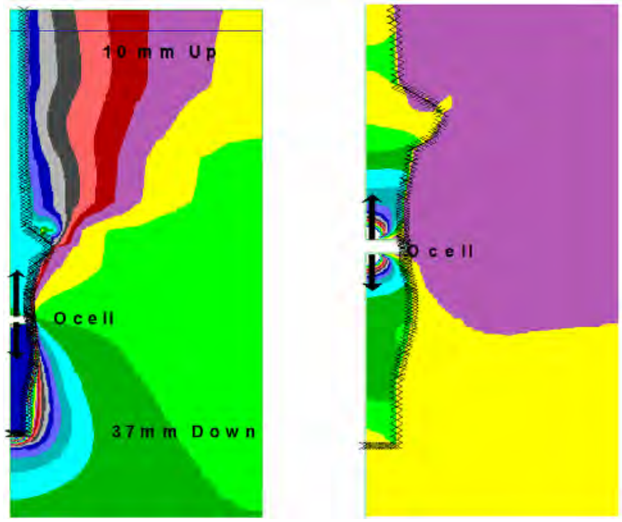

Figure 12a Figure 12b

Figure 12. Contours of a) Vertical Displacement and b) Major Principal Effective Stress For Model of O-cell Test on Irregular Shaped Pile (Case Oi) under 9,000 kN O-cell Load

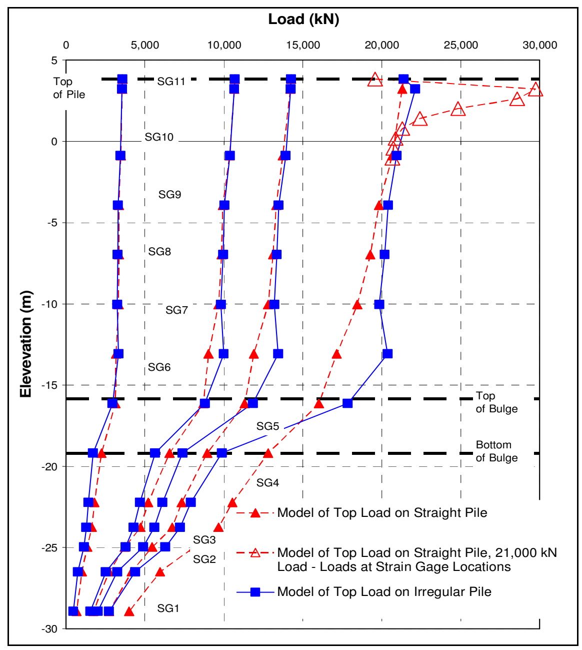

Figure 13. Load Distribution in Models of Top Loading of Irregular and Uniform Shape Piles

The load-deflection curves for top loaded piles, for both the irregular and uniform shape piles are shown in Figure 14. These curves have been developed in 2 ways:

- By calculating an “equivalent” top load curve from the O-cell models, Cases Oi and Ou. The method used to develop the equivalent top load curve are described in O-cell test reports, but essentially amounts to taking the sum of the upward and downward O-cell loads at the same displacement and then correcting for the buoyant weight of the pile and its elastic compression.

- By analyzing a top load model where the O-cell is removed and the pile is loaded from the top, Cases Ti and Tu.

The model results plotted in Figure 14 show that there is an initial large (approximately 4 mm) displacement during the first load increment in the FLAC model for both the irregular and uniform pile.

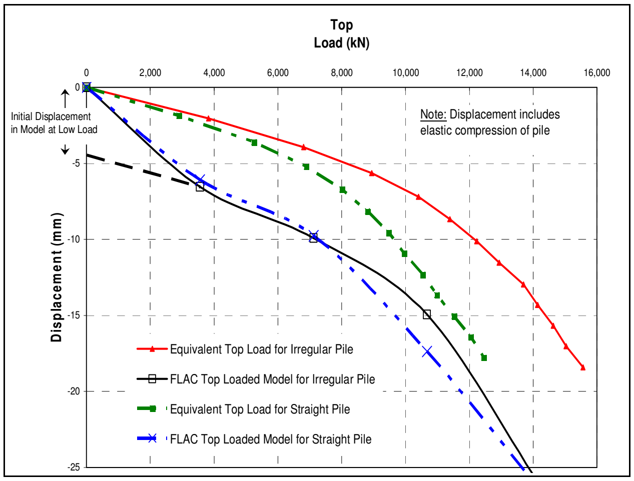

Figure 14. Load-Deflection Curves for Top Loading of Irregular and Uniform Shape Piles

In Figure 15, the load deflection curves from the model are adjusted by removing this initial displacement. The adjusted load-deflection curve for the model of the uniform shape pile is in extremely good agreement with the equivalent top load curve, but for the irregular shape pile the adjusted curve for the top-load model is still considerably softer than the equivalent top load curve.

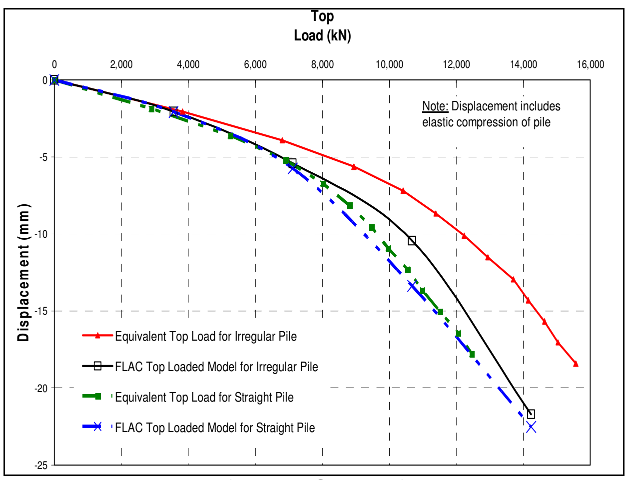

Figure 15. Load-Deflection Curves for Top Loading with Model Result Adjusted to Remove Initial Displacement in Model at Low Load

The initial large displacement in the top load models may be the result of the limitations in the modeling method described above, particularly the fact that residual shear stresses due to concrete curing are not incorporated in the model. Additional data and modeling work would be required to incorporate residual shear stresses in a more rigorous manner in the FLAC model. However, it is noted that the model was calibrated to the irregular shape pile, which may also affect the comparison between the equivalent top load curve and the curve resulting from the top loaded model. Additional study is required to evaluate this comparison further, for example by calibrating a model to the results of O-cell testing of a uniform pile.

4.4 Conclusions Derived from Model Results

The following conclusions have been drawn from the modeling work presented above:

- The presence of an irregularity, such as a bulge, in a concrete pile appears to have a significant impact on the results of load tests. In this case, the bulge causes the upward movement of the top of the O-cell to be half what it is for a uniform pile.
- Load distributions and load-deflection curves for both O-cell and top loaded piles are also significantly affected by a significant irregularity.
- Stress concentration in the pile can be caused by loading with ram that has a significantly smaller diameter than the concrete pile. This effect can be mitigated either by designing strain gage locations to be far enough from the loading device to avoid stress concentration, and/or by using multiple rams or O-cells to apply the load to larger piles
- It appears that the top-load model over-predicts the settlements of a pile with significant irregularities when compared with the equivalent top load curve derived from the actual O-cell test on the pile. However this conclusion may be a result of the limitations of the numerical model and requires additional assessment.

The case studies and modeling presented herein clearly demonstrate that knowledge of the actual pile dimensions is very important in interpreting load test results and developing recommendations for pile capacity, and the sonar caliper is a tool that can provide this important information.

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