Prediction of Defects and Capacity of Drilled Shafts in Varved Clays

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In recent years, drilled shafts have become a cost-effective replacement to driven piles. Nevertheless, several questions are often raised when dealing with drilled shafts, due to the inherent construction techniques. These questions include:

• What is the effect of caving and necking on the structural capacity of drilled shafts, and where and how many will cause the shaft to fail prematurely?
• How well do present design methods estimate the ultimate capacity of drilled shafts? Also are new and/or sophisticated design methods more accurate than classical approaches?
• Are defects in drilled shaft construction accurately detectable using non-destructive testing (NDT)?
• How well does Statnamic load testing approximate static load test results, particularly in unusual materials such as varved clays?
• What is the effect of construction defects on the lateral load capacity of drilled shafts?

An effort to study these issues in the form of a full-scale field test at the National Geotechnical Experimentation Site (NGES) located at The University of Massachusetts in Amherst is ongoing. The program consists of the installation of six (6) drilled shafts, some with built-in defects. The installation took place between March 20 and 24, 2000. Load testing using both lateral and axial conventional and Statnamic methods is planned for summer 2000.

This effort is organized by the Geo-Institute Deep Foundation Committee, with materials and supplies graciously provided by ADSC Contractor Member Hub Foundation Company, Inc. of Harvard, Massachusetts in cooperation with the International Association of Foundation Drilling (ADSC). The Federal Highway Administration provided funding for instrumenting the shafts, and for facilitating the work.

Site Conditions
The NGES Amherst site consists of two separate locations. The older of these two locations has been used extensively for foundation research. This project is located at the new site which is situated approximately 500 m (550 yards) to the south of the older site. The site is underlain by deep soft Connecticut Valley varved clay deposits extending approximately 37 m (120 ft) in depth. The varved clay is overlain by a crust of over-consolidated clay, silt, and fill, which is approximately 4.5 m (15 ft) thick (Fig. 1). The Varved clays have a Plasticity Index of 17 to 22 with Undrained Shear Strengths of 34-38 kPa (710 psf-800 psf). The reported N-values are on the order of 1-2. The geotechnical data is available for download from the NGES web site (http://www.unh.edu/nges).

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Construction

Shafts were built at a distance of 5D from one another to avoid any possible group effect. Six drilled shafts were installed (Fig 2 and 3). All shafts were installed with a Soilmec R-515* hydraulic rotary drill rig. To facilitate construction, a 900 mm (36 in) diameter hole was augered to a depth of approximately 6 m (20 ft). A 1 m (40 in) outer diameter temporary casing was inserted in the augured hole. Next, a 900 mm (36 in) diameter hole was augered through the casing to a final depth of 14.3 m (47 ft) below grade. Below the casing, shafts were drilled open hole without the use of slurry. The shaft remained open for several hours without the accumulation of more than 50 mm (2 in) of water prior to pouring concrete. The shaft bottoms were soundened prior to concrete placement. Concrete having a 28-day compressive strength of 35 MN/m² (4,000 psi) was placed using the free fall and tremie methods as indicated in Table 1. Twelve test cylinders were collected from every shaft.

Reinforcement, placed prior to concrete placement, consisted of 10 #9 bars (28.5 mm, 1.125 in) and #4 (12.5 mm, 0.5 in) stirrups, located 45 cm (18 in) on center. Select reinforcement was replaced by similar sized Dywidag* threadbar to facilitate load testing. All reinforcement was full length. Four 2-in ID black iron pipes were installed, for cross-hole sonic logging, in all test shafts except one shaft where only three were installed, to study the effect of tube placement on NDT results.

Instrumentation

Test shafts are instrumented according to Table 1 using strain gages mounted on #4 (12.5 mm, 0.5 in) sister bars, with two sister bars 180 degrees apart, perpendicular to the reaction beam, at each level. In addition, stainless steel telltales were installed, one per strain gauge level, for use during load tests. Two accelerometers were also installed for use during static load testing.

Defect Detection Program

Over the last 10 years the number of firms offering non-destructive testing of drilled shafts has increased greatly. Defects were engineered in the built shafts in order to perform blind tests of these systems. Several types of defects were integrated into the shafts including necking, holes, caving, and soft bottoms. The "shell" of the defects was formed using a variety of materials rigidly attached to the rebar cage. The materials included 1-10 gallon plastic pails, foam insulation, 9-13-inch diameter cardboard construction tubes, and 4-inch flexible drain pipe (Fig. 4 & 5). Some anomalies were filled with in-situ soils to replicate inclusions on side walls, others were left empty to simulate slurry pockets. Anomaly size and locations were documented by the authors. Seven organizations replied to our Class-A defect prediction program (see side bar). The respondents represented some of the best known firms and universities in the field. NDT predictors were invited to test the drilled shafts at anytime following the construction. Drilled shafts were typically tested 7-21 days following construction. Black iron

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Figure 1 Soil Profile

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As expected the preliminary results indicate CSL is more reliable than SE. The data has not been fully analyzed, however some preliminary observations can be made. Most large defects were located by all detectors. However, we were disappointed that some detectors report poor concrete quality, where there was no built in defect, or known concrete segregation.

Load Test Program
Load testing has been scheduled to be performed as you are reading this issue of Foundation Drilling Magazine. Two shafts, one defect and one non-defect (No. 2 & 4) will be load-tested according to ASTM D1143-81 Standard Test Method for Piles under Static Axial Compressive Load (Section 5.6 Quick Load Test Method for Individual Piles). Static load testing will be performed on Shaft No. 6, as well as other test shafts. Lateral load testing is also planned for a later date.

Capacity Predictions
Predictions of the ultimate capacity are being solicited using a variety of design methods, from all interested parties. Predictors are encouraged to provide the ultimate capacity; and axial load distribution along the length of the pile: 50% and 100% of ultimate capacity; and axial load settlement curves of the shaft's tip and top. Interested readers should contact the authors as soon as possible to obtain a prediction package.

Who Made This All Possible
This work could not have been performed without the generosity of Jim Maxwell, president and owner of Hub Foundation Company (Fig. 7). We are also very grateful to the Federal Highway Administration not only for its financial sponsorship of the work, but also for the active roles of Carl Ealy and Al DiMillio in bringing this work to fruition. We are grateful to S. Scot Litke and the rest of the ADSC staff for introducing us to Hub Foundations, and for shepherding the project. Members of the ASCE Geo-Institute Deep Foundations Committee helped conceive this project. In particular we are grateful to Mike O'Neill, University of Houston, Len Cob, Mohamed Hessein, GRL, and Dan Brown, Auburn University for their advice. We are also grateful to UMASS faculty and students for their assistance.

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Several NDT methods were used by the predictors to locate defects including Cross-Hole Sonic Logging, and several variations of Sonic Echo Testing.

Several anomalies designed to replicate construction defects including necking, caving, and voids.
### Table 1: Shaft Details

<table>
<thead>
<tr>
<th>Shaft 1</th>
<th>Shaft 2</th>
<th>Shaft 3</th>
<th>Shaft 4</th>
<th>Shaft 5</th>
<th>Shaft 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Shaft</td>
<td>Test Shaft</td>
<td>Reaction Shaft</td>
<td>Test shaft</td>
<td>Reaction Shaft</td>
<td>Statmatic Test Shaft</td>
</tr>
<tr>
<td>Engineered Defects</td>
<td>No Engineered Defects</td>
<td>Engineered Defects</td>
<td>Engineered Defects</td>
<td>Engineered Defects</td>
<td>No Engineered Defects</td>
</tr>
<tr>
<td>2 levels of foil sister bars</td>
<td>5 levels of foil sister bars</td>
<td>2 levels of foil sister bars</td>
<td>5 levels of foil sister bars</td>
<td>5 levels of vibrating wire sister bars</td>
<td>5 levels of foil sister bars</td>
</tr>
<tr>
<td>2 levels telltales</td>
<td>5 levels telltales</td>
<td>2 levels telltales</td>
<td>5 levels telltales</td>
<td>2 levels telltales</td>
<td>no telltales</td>
</tr>
<tr>
<td>Tip</td>
<td>Acclerometer</td>
<td>Full length</td>
<td>Full length</td>
<td>Full length</td>
<td>Full length</td>
</tr>
<tr>
<td>Inclinometer Casing</td>
<td>Full length</td>
<td>Casing</td>
<td>Inclinometer Casing</td>
<td>Inclinometer Casing</td>
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</tr>
<tr>
<td>4 NDT pipes</td>
<td>4 NDT pipes</td>
<td>3 NDT pipes</td>
<td>4 NDT pipes</td>
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<td>4 NDT pipes</td>
</tr>
<tr>
<td>Concrete placed by tremie</td>
<td>Concrete placed by free fall</td>
<td>Concrete placed by tremie</td>
<td>Concrete placed by free fall</td>
<td>Concrete placed by free fall</td>
<td>Concrete placed by tremie</td>
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</tbody>
</table>

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In particular we would like to thank Shawn Kelley, Alan Lutenegger, Bob Mokowa, and Carlton Ho. Special thanks to Grey Mullen, of USF and Pierre Gouvin of Slope Indicator Company for their assistance and advice. Credit is also due to Gil Peel of American Equipment and Fabricating Corporation for providing a substitute Soil Mec drill rig, when one became necessary.

NDT Participants

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- GZA Geoenvironmental, Inc.*
- Olson Engineering, Inc.*
- STS Consultants, Inc.*
- ADSC Member

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Interested readers should contact the authors as soon as possible to obtain a prediction package.

Conclusions

We are not ready to provide you, or the sponsors, with engineering conclusions at this time. This is not the last you will hear from us on this important subject. However, at this time we can conclude that it has been a pleasure working with Hub Foundation President, Jim Maxwell; Carl Ealy and Al DiMillio of the FHWA Geotechnical Research Division; Shawn Kelly of the University of Massachusetts; S. Scot Litke, ADSC Executive Director; Gray Mullen, University of South Florida, and the rest of the people involved in this project.

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