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## **Grouted Helical Piers for Use in Foundation Rehabilitation: Considerations for Small-Scale Centrifuge Testing**

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**SUMMARY:** Rehabilitation of building structures is a critical need facing numerous older urban areas. Many of these structures are supported on pile groups, which do not have adequate load capacity to support the demands expected after rehabilitation or superstructure replacement. Consequently, practical methods for strengthening existing foundations are of paramount concern. Recent studies have focused specifically on the use of grouted helical pier systems to strengthen pile group foundations, thereby substantiating their potential as a technique for load capacity enhancement (see companion paper by Laefer and Manke, 2006). However, these scaled studies were conducted at one-g level, resulting in soil confining stresses lower than those expected in the field. Thus, further verification through numerical modeling; full-scale experiments, or centrifuge testing is needed. This paper presents preliminary issues related to developing tools to support centrifuge testing of grouted helical pier systems. For this study, models for a 15-g centrifuge test were first explored at the one-g scale. With the small-scale model piers, a variety of grout types and pier installation methods were considered for the design and evaluation of the centrifuge tests. Based on the findings from this one-g testing, a preliminary centrifuge testing plan is presented.

**Keywords:** Capacity enhancement, centrifuge models, foundation rehabilitation, helical pier, model testing, and ultra-fine cement grout.

### **INTRODUCTION**

Enhancement of building foundations plays a critical role in urban rehabilitation. Capacity enhancement of in situ foundations may be required to accommodate additional loads during expansion or replacement of old structures, where the foundations of previously demolished structures can or must be used (Hertlein and Walton, 2000). To this end, effective approaches to strengthening existing foundations are of paramount concern in engineering practice.

Helical piers have been widely used in foundation retrofit as structural underpinning elements for remediation of excessive building movement (e.g. Perko and Rupiper, 2000). Helical piers are attractive due to their rapid installation and minimal equipment needs (e.g. Pack, 2000; Prasad and Rao, 1996). If the traditional solid shaft of the helical pier is replaced by a hollow one, grout can be pumped through the system. Manke

(2004) proposes the term – Grouted Helical Pier Systems (GHPS), to collectively describe a number of patented and non-patented arrangements involving a cementitious grout and a helical pier. Recent studies have evaluated GHPS for strengthening pile group foundations, substantiating their potential as a technique for load capacity enhancement (Vickars and Clemence, 2000; Manke, 2004; Laefer et. al, 2005). However, the latter two studies were both conducted at a one-g (acceleration of gravity) level, at less than full scale, resulting in soil confining stresses lower than those encountered in the field. To simulate the installation and load transfer mechanisms of GHPS without full-scale testing, small-scale centrifuge pier models provide an economical, alternative approach, whereby prototype soil confining stresses can be preserved. In addition, detailed measurements during centrifuge testing and physical exploration (e.g. after construction and/or loading) of the GHPS in a controlled laboratory, after centrifuge testing, can be used to evaluate performance. However, centrifuge testing of GHPS is complicated by the small scale of the pier elements and the dual installation processes of driving the helical pier and grouting. A limited amount of work has been done on centrifuge grouting but was concentrated on compaction grouting, which is a fundamentally different process (Nichols and Goodings, 2000).

### SCOPE OF THIS STUDY

In this work, we first present a review of techniques used in practice for the installation of helical pier grouted systems. Given the potential variety of methods used in practice, this information is important when designing the model centrifuge experiments. Subsequently, practical issues related to the centrifuge experiments, such as the small size of the model piers and the model grout, are evaluated by conducting experiments at the one-g level. We then present the development and construction of a series of instruments and tools that were used in the real investigation in the centrifuge. To capture the resulting mechanisms of grout transfer into the soil, a variety of grout types and pier installation methods were tested at one-g in small buckets. Finally, the centrifuge test plan and preliminary results are reported at the end of the paper.

Understanding the scaling laws relating engineering parameters of model and prototype in the centrifuge is critical. Table 1, reproduced from Kutter (1992), presents the basic scaling laws for engineering parameters of interest. As will be described later, in an  $N = 15$  (15-g) centrifuge experiment, the dimensions of a model pier are considerably small (0.25 inch outer-diameter in this case).

Table 1. Centrifuge scale factors for basic engineering parameters (after Kutter 1992).

<b>Parameters</b>	<b>Symbols</b>	<b>Scale factors<sup>1</sup></b>
Acceleration, Gravity	a, g	N
Density	$\rho$	1
Length	L	1/N
Mass	M	1/N <sup>3</sup>
Force	F	1/N <sup>2</sup>
Stress, Strength	$\sigma$ , s	1
Strain	$\epsilon$	1
Time (Dynamic)	T	1/N
Frequency	F	N

<sup>1</sup>  $N = \lambda_m \lambda_p$ , where  $\lambda$  = parameter of interest for prototype ( $p$ ) and model ( $m$ ), respectively.

## **REVIEW OF TECHNIQUES USED IN PRACTICE**

Given the potential variety of methods used in GHPS installation, an industry survey was conducted and used to guide the design of the centrifuge experiment. The survey was distributed to the 33 non-academic members of the Deep Foundation Institute's Helical Foundations and Tiebacks Committee and reflects 18 responses (Laefer, 2006). The goal of the survey was to document the current state of usage and installation details of grouted helical piers in the United States. Although usage of the grouted version was by no means predominant, nearly all respondents reported using them at least occasionally. The survey requested information regarding pier dimensions, grout mixes, installation methods, typical usage, and performance expectations.

### **Pier dimensions**

Helical piers are comprised of a pipe 2.38 in (60.45 mm) to 10.75 in (273.05 mm) in diameter, with a tendency towards the smaller sizing but starting at 3.5 in (88.9 mm) with at least one helix. Helices ranged from 6 in (152 mm) to 16 in (406 mm), with most being in the 8 in (203 mm) to 12 in (305 mm) diameter range. Spacing between the helices was recommended as 3 ft (914 mm), 3 times the diameter of the lower helix ( $D_h$ ), or  $3D_h$  plus the pitch of the helix, and the orientation of the helices must be offset by  $180^\circ$  to ensure both helices cut the same path in the soil.

### **Grout mixes**

The preferred grout mix ranged from a neat Portland cement to a silica fume mix. For small diameter grouted columns [ $<178$  mm (7 in) in diameter], the following was alternatively recommended: 94 lbs (43 kg) of Portland Cement (Type I or II), with 15–20 lbs (7–9 kg) of silica fume (preferred) or flyash, and a superplasticizer capable of producing a cone flow time of 20–30 seconds (ASTM C939 Cone Flow Test), which is approximately 5–15 ounces/bag (142–425 g/bag) of cement, and an expansion agent capable of generating a minimum expansion of 2.5% (percent by unconfined volume, as per ASTM C940). The resulting mix has a 2 hour pot life at  $70^\circ\text{F}$  ( $21^\circ\text{C}$ ), a 3,000 psi (20.7 MPa) strength at 4 days, and a 5,000 psi (34.5 MPa) strength at 28 days. Where expansion was not required, only the use of the Portland cement, along with fine sand (50% by volume), and fiber-mesh [1 lb/cy ( $0.45\text{ kg/m}^3$ )] was proposed.

### **Installation methods**

Grout was most commonly installed at atmospheric pressure, although pressures up to 20 psi (138 kPa) were cited. Increasing the placement pressure with depth was mentioned but not quantified. The most important aspects regarding a quality installation ranged from achieving the final positioning and alignment with the required tolerances to maintaining a consistent penetration of one helix-pitch length [typically 2.5 to 3.5 in (63.5 to 76.2 mm)] for every  $360^\circ$  of rotation, thereby ensuring that the grout fully filled the shaft. Slower or faster penetration rates have been linked to significant soil disturbance, leading to lower bearing capacities.

### **Typical usage**

The choice to include grout in conjunction with a helical pier is driven mostly by the need to strengthen the piers in loose or soft soils against buckling, although some respondents cited a desire to increase axial capacity as an additional factor. Soil types were only generally described as loose or soft, except for one respondent who offered the following as a practical guideline, "Soil with Standard Penetration Test (SPT) blow counts per ASTM D-1586 of 4 blows/ft (13 blows/m) or less along the entire embedded

length of the helical pile shaft will require a greater, solid cross-section to prevent buckling. More specifically, grouted shafts are used in clay with consistencies from very soft to medium [ $0 < \text{cohesion} < 500 \text{ psf}$  ( $3.4 \text{ MPa}$ )], or very loose sand [ $(\phi < 25^\circ$  or  $\gamma_{\text{dry}} < 85 \text{ pcf}$  ( $1361 \text{ kg/m}^3$ )]". The same source reported that more recently, grouted shaft helical piers have been successfully installed in overburden soil with SPT blow counts greater than 10 blows/ft (33 blows/m). In this case, the grouted shaft is being used to develop greater load capacity and a stiffer response – not necessarily to prevent buckling. A practical limit of soil with an SPT blow count equal to or less than 20 blows/ft (66 blows/m) is proposed, because of the difficulty of driving the helical piers through the material.

### **Performance expectations**

Since helical piers have been considered generally as end-bearing elements, and the grouting has been considered primarily as a method to increase stiffness, little attention has been paid to the final, composite pier-grout diameter. Survey respondents indicated axial load capacity was observed to increase from 1.4 to double that of the ungrouted pier, as determined from a 4-day field test.

## **PRIMARY INSTRUMENTS AND GROUT COMPOSITION**

### **Model Helical Pier**

Prototype helical pier dimensions were selected based on technical documents provided by Precision Pier, USA (Precision Pier, 2005). Prototype piers are constructed of a 4 in (102 mm) diameter round tube shaft with 1 or 2 helices of 16 in (406 mm) diameter and 3 in (76 mm) pitch. Centrifuge scaling laws, considering a 15-g model (Table 1), resulted in model helical piers with a 0.25 in (6.35 mm) O.D., a 0.22 in (5.59 mm) inner diameter (I.D.), a 12 in (405 mm) long stem made of round brass tubing, and a helix of 1 in (25 mm) diameter, with a 0.2 in (5.1 mm) pitch (Figure 1).

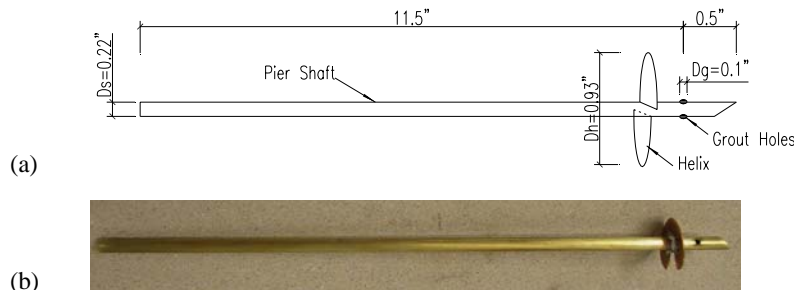


Figure 1. Model helical pier: (a) schematic and (b) photograph of constructed pier.

### **Pressurized grout chamber**

A grout delivery mechanism was designed to provide variable pressure control and easy filling of a one-g model pier-soil system. It included a pressurized air valve, a pressure controller, a two-piece PVC tube grout chamber [the chamber is 4 in (10 mm) diameter, 10 in (25 mm) high, with a total volume capacity of  $125 \text{ in}^3$  ( $0.002 \text{ m}^3$ )], and a pressure gage. PVC tubes were selected for their ease of mating (top and bottom pieces) and cleaning. A safety pressure valve atop the grout chamber was used to prevent the internal pressure from exceeding the gage limit. Figure 2 shows the grout pump system.

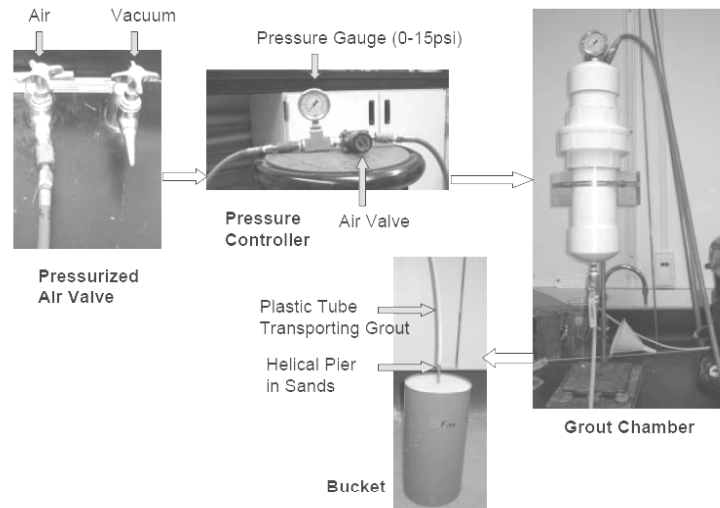


Figure 2. Grout pump system

### Soil selection

In centrifuge testing, very fine sands are typically selected; however, for this application very fine grain sand would limit the permeation of grout into the soil. Grouting is typically controlled by the effective size ( $D_{10}$ ) of the soil gradation curve. To minimize clogging and assure permeation into the soil, sands of increasing effective grain size were tested starting with Nevada sand 120, 90, and 60, to Silica sand #30 ( $D_{10}$ : 0.09 mm, 0.13 mm, 0.13 mm, and 0.31 mm respectively). Comparison between the grout installations in Nevada sand 60 and Silica sand #30 will be discussed in subsequent sections. For Nevada sand 120 and 90, severe clogging problems were encountered regularly at the soil/pier interface. The Silica sand #30 had the most repeatable delivery and largest volume of placed grout and, as shown in Figure 3, which was similar to that used by Nichols and Goodings (2000).

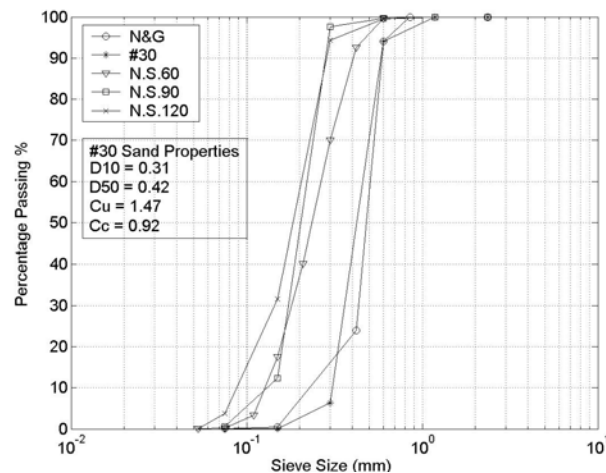


Figure 3. Grain size distribution curves for Nevada sand (N.S.) 60, 90, 120, Silica sand #30 and Nichols and Goodings' (2000) sand (N&G)

### Grout mix design

The grout was delivered through the model pier shaft into dry sand of various sizes as noted above. To promote scale consistency between the grout and surrounding soil, as compared to field applications, ultrafine cement was selected for the model grout.

Ultrafine cement has a mean grain size typically 0.14 – 0.20 that of ordinary Portland cement (3.14 – 4.42  $\mu\text{m}$ ). The ratio of the exit hole diameter ( $D_e$ ) in the pier to the mean grain size ( $D_{50}$ ) of the ultrafine cement ( $D_e/D_{50}$ ) ranges from 575 to 809. The larger this ratio is, the less likely clogging at the exit hole will occur.

Different grout mixes were investigated for fluidity, permeability, and compressive strength. Four candidate grout mixes were considered (Table 2). Additives were included to reduce the water content, improve fluidity, and minimize bleeding and segregation. During centrifuge testing, there is a delay of approximately 20 minutes from activating the centrifuge system to its reaching target acceleration level. A goal of this research was to “grout in flight” (while the centrifuge was spinning), to assure grouting into prototype soil conditions, therefore, the mix had to have a sufficiently long pot life to permit proper placement. Therefore, the fluidity of the grout mix over time was quantified using a flow cone test (ASTM C939). Five flow cone run-out times were recorded every 15 minutes over a one-hour duration (Figure 4). After one hour, Grout Mix C had the shortest flow cone run-out time and minimum viscosity change: 18 seconds at 15 min and 22 seconds at 60 min. Grout Mix B at 60 minutes was too thick to flow through the flow cone.

Table 2. Grout mix summary

Grout mix type	Cement	$D_e/D_{50}$	Water cement ratio (w/c)	Pozzalite Clay	Water reducing additive
A	TXI block cement	170	0.80	5%	Adavaflow: 1%
B	TXI block cement	170	0.70	2%	Adavaflow: 1%
C	Ultrafine cement	690	0.45	0%	Mighty-150: 1.5%
D	MC-500 cement	600	0.45	0%	NS-200: 1.5%

Note: The percentages are by weight of cement

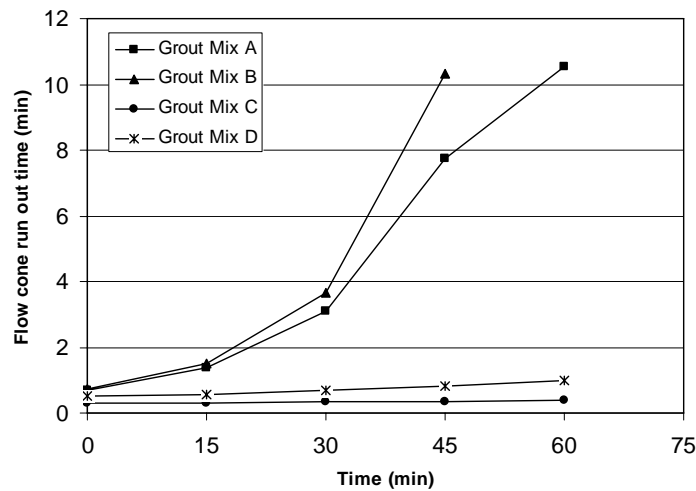


Figure 4. Flow cone run-out time vs. time based on Marsh cone experiments.

The 3-, 7- and 14-day compressive strengths of Grout Mix C were 2,300, 4,700, and 4,900 psi (15.9 MPa, 32.4 MPa and 33.8 MPa), respectively, the highest among the four-candidate grout mixes. All candidate mixes had only minimal bleed and segregation after one-hour.

## ONE-g BUCKET TESTS

### Experimental setup

To investigate the grout and grout-pier system installation methods, a series of tests were conducted at one-g using the model piers and dry sands pluviated into 5-gallon buckets. These tests also served to evaluate the performance of the grout mix in the Nevada sand 60 and the Silica sand #30. Air pluviation was used to achieve a 75% relative density for both sands by suspending a hopper 39 in (991 mm) above the top of the sand surface in the bucket. Using a flexible hose with a sieve manually moved across the bucket surface area, air pluviation placement took approximately 50 minutes to deliver 3.5 ft<sup>3</sup> (0.1 m<sup>3</sup>) of sand.

Three different pier-grout installation schemes were considered (Figure 5). In Scheme I, the grout installation used a model helical pier as shown in Figure 1. In Scheme II, the pier shaft was installed without the helix. The third scheme differed from the second only in that an additional two sets of grout holes were drilled to increase the volume of deliverable grout.

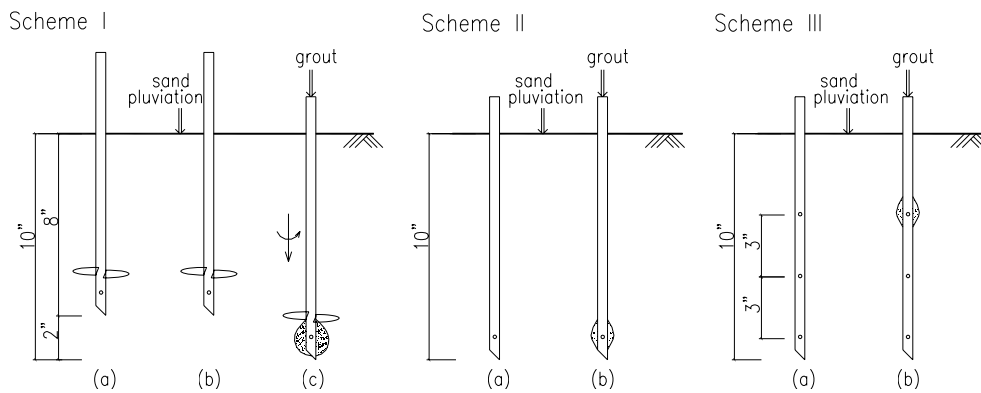


Figure 5. Schematic of the three installation schemes

In Scheme I, the model helical pier was first suspended vertically in the center of the bucket. Sand was then pluviated into the bucket surrounding the pier, until the pier end was embedded 8 in (203 mm) into the sand. This mimics the centrifuge installation process, where soil was first placed at one-g around the model piers (it is not currently possible to install the piers in flight). Since the grout is installed at the same time as the pier is torqued, the effects of pier driving on soil confining stresses may be assumed minimal, compared with the soil modifications due to grout permeation. While torquing the pier at approximately 7–8 revolutions per minute (rpm), the grout was simultaneously delivered into the shaft from the grout chamber. During this torquing process, the helix drew the pier shaft approximately 2 in (51 mm) further into the sand. For the pier shaft only cases (Scheme II and III), the shafts were embedded in the pluviated sand medium to a depth of 10 in (254 mm). Without any torque application, the grout was directly pressured into the shafts. In the above procedures, a constant grout chamber pressure of 12 psi (83 kPa) was maintained.

### Results and discussion

Each method was repeated at least seven times using Grout Mix C in both the Nevada sand 60 and Silica sand #30 (Table 2). The buckets were excavated three days after grout installation, and physically inspected. Results are summarized as follows:

- In Scheme I, the grout bulbs in the Nevada sand 60 were on average 1 in (25 mm) in diameter (4Ds) and approximately 1 in (25 mm) long; in Silica sand #30, grout



bulbs were approximately 2 in (51 mm) in diameter (8Ds) and 3 in (76 mm) long (Figure 6a and 6b).

- For pier shafts with one set of holes used in Scheme II, grout bulbs in Nevada sand 60 were around 0.5 in (12.7 mm) in diameter (2Ds) and 0.5 in (12.7 mm) long. In Silica sand #30, grout bulbs were approximately 1.25 in (31.75 mm) in diameter (5Ds) and 1 in (25 mm) long (Figure 7b and 7b).
- For pier shafts with three-sets of holes in Scheme III, the grout bulbs were similar to those in Scheme II. Observations showed that the lower two holes did not work well. The grout bulbs generated in the top holes from Scheme III were dimensionally similar to those in Scheme II.
- Each of these installation methods was highly repeatable, with similar grout sizes and geometries for individual runs of a given method.

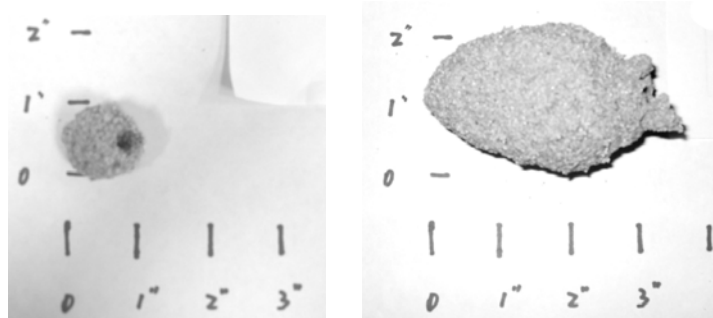


Figure 6. (a) Left: Grout bulb from Scheme I grout installation in Nevada sand 60 soil  
(b) Right: Grout bulb from Scheme I grout installation in Sand #30 soil

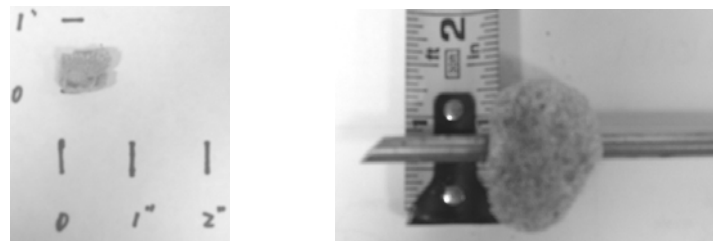


Figure 7. (a) Left: Grout bulb from Scheme II grout installation in Nevada sand 60 soil  
(b) Right: Grout bulb from Scheme II grout installation in Sand #30 soil

## **SUMMARY REMARKS**

Based on a review of U.S. practice, model helical piers were constructed, and grout composition and installation of grouted, helical piers were investigated, to design centrifuge experiments. Grout delivery through model piers, was considered using different one-g testing schemes in pluviated dry sand. The presence of a helix during grout delivery resulted in approximately eight times more delivered grout volume; secondly, the grout volume delivered in the Silica sand #30 was approximately 12 times that in Nevada sand 60; and thirdly, additional sets of grout holes aligned on the pier shaft proved unnecessary. The largest grout bulbs obtained (approximately eight times that of the pier shaft diameter) were obtained when using the Silica sand #30 and pier with helix. These results provide insight into which pier-helix configurations, sand

gradations and grout mixes (with ultrafine cement) are suitable for small-scale centrifuge experiments.

### Centrifuge test plan and preliminary results

Based on the one-g studies, centrifuge tests designed and recently completed in June 2006. The model container test plan is shown in Figure 8. A Flexible Shear Beam (FSB) soil container of 67.8 in (1.72 m) long, 27 in (0.69 m) wide, and 27.5 in (0.70 m) deep was used. To maximize grout delivery volume, silica sand #30 was first pluviated to a dense condition and the Type C ultrafine cement grout with w/c ratios of 0.45 and 0.6 were used. Schemes I and II, as proposed in the previous section, were studied in the centrifuge; furthermore, two new variables, pier embedment depth and grout delivery pressure (via an air pressure system), were investigated.

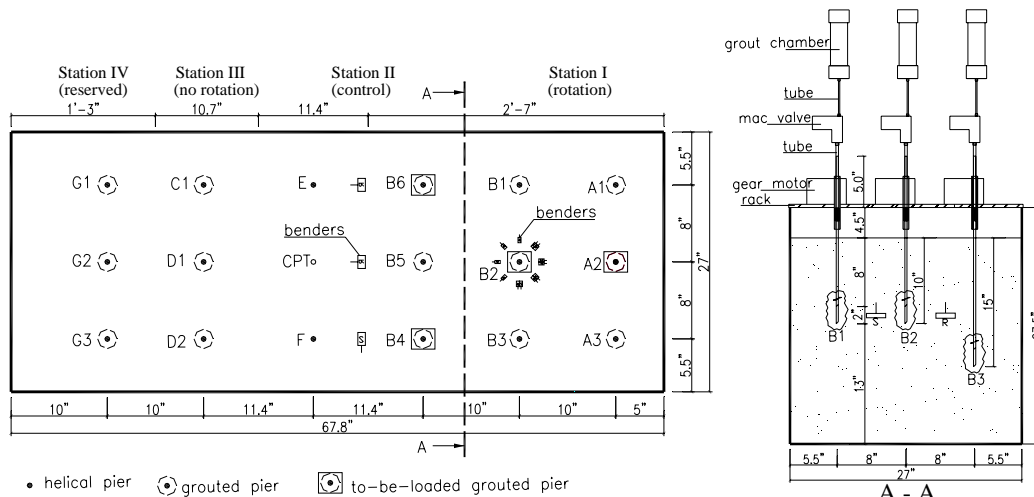


Figure 8. Centrifuge test plan and elevation (all units in model scale, inches).

For centrifuge testing, the piers were placed (with and without a helix) in the container, with only nominal embedment and the sand was pluviated across the container to an elevation of 23 in (584.2 mm). After spinning to the target centrifugal acceleration of 15-g, the grout was delivered to individual piers in sequence, through local chambers mounted on top of each pier. Torque was applied simultaneously with select model piers. After at least seven days of grout curing, the grouted pier units were carefully excavated and physically examined (Figure 9). Investigation into the effect of the test variables (e.g. grout installation with or without the torque) is being performed, and these results will be reported in the near future.

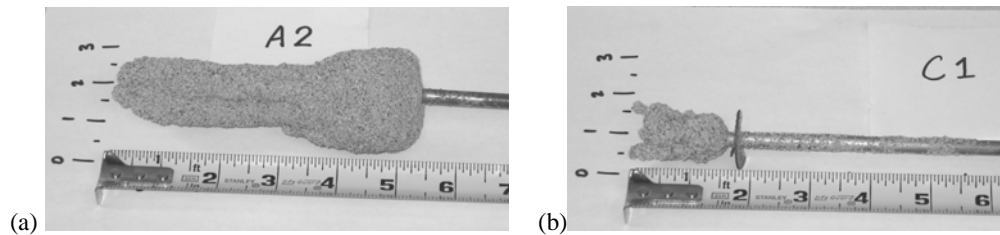


Figure 9. Photographs of grouted pier units: (a) grout installation *with* torque and (b) *without* torque.

### ACKNOWLEDGMENTS

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