Failure of Axially Loaded Augered Cast-in-Place Piles in Coastal South Carolina

Fracaso de pilotes de barrena continua cargado axialmente en la costa de South Carolina

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Abstract

Five augered cast-in-place piles bearing in a stiff Coastal Plain formation of South Carolina were load tested using the conventional top-loaded setup. Four of the five test piles failed well below the predicted ultimate compressive capacity. Interpretation of the load test results suggested that the test piles were damaged during testing, and this conclusion was supported by the results of pile integrity testing. Numerical analysis indicates that even small eccentricities developing within the pile section could lead to damage at higher axial compressive loads. The lessons learned are: (1) augered cast-in-place piles can exhibit eccentricity that is inherent to the construction process; (2) high axial compressive loads applied during load testing can intensify eccentricity effects; (3) unreinforced augered cast-in-place piles can be vulnerable to damage from shear and moment forces, and; (4) successful design should consider the potential for eccentric loads during load testing and during application of the superstructure loads.

Resumen

Cinco pilotes de barrena continua fueron perforados en una de las formaciones más firmes de la llanura costera de South Carolina. Se realizó una prueba en la cual los pilotes fueron cargados superiormente de una manera convencional. Cuatro de los cinco pilotes fracasaron muy por debajo de la resistencia última en compresión calculada. La interpretación de los resultados de las pruebas sugirieron que los pilotes fueron dañados durante los ensayos; esta conclusión fue respaldada por los resultados de las pruebas de integridad de los pilotes. El análisis numérico indica que, debido a las cargas compresivas axiales más altas, aún pequeñas excentricidades en la sección del pilote podrían provocar daño. Las lecciones a aprender son: (1) los pilotes de barrena continua pueden exhibir excentricidades que son inherentes a la construcción, (2) las cargas compresivas axiales altas utilizadas en un ensayo pueden intensificar los efectos de las excentricidades, (3) por efecto de momentos, los pilotes de barrena continua sin armadura pueden ser vulnerables al daño, y (4) el diseño exitoso debe considerar la posibilidad de tener cargas excéntricas durante una prueba y durante aplicación de las cargas del edificio.

1 INTRODUCTION

This case history paper describes the failure and subsequent engineering investigation of augered cast-in-place test piles at a site along the coast of South Carolina. As will be described herein, the mechanics associated with the test pile failures involve basic principles of solid mechanics. And although such principles are part of every civil engineering curriculum, the failures still occurred. It is with this understanding that the authors intend to expand the discussion of these test piles to include comments on the role of failure in engineering practice.

1.1 Project Description

The project site is located in Conway, South Carolina, approximately 15 km (9 miles) northwest of Myrtle Beach. The project is an expansion to the existing water treatment plant that consists of three new oxidation ditches. These new oxidation ditches cover a plan area of approximately 18 m by 49 m (60 ft by 160 ft).

1.2 Geotechnical Characterization

S&ME, Inc. (2001) performed characterization of the subsurface conditions for design purposes. In general, the conditions encountered during the field exploration are representative of the South

Carolina coast. Poorly graded sands are present in the upper 3.6 m (12 ft), and these sands are underlain by the Pliocene Bear Bluff formation. The Bear Bluff formation, which is part of the Coastal Plain Sedimentary Wedge, is described as shell beds with thick beds of blue-green to dark gray, very clayey silt (Campbell, 1992; Dubar, 1969; Ward *et al*, 1991). The very clayey silts are actually complex intercalations of sand and silty clay beds.

Groundwater was encountered within 1 m (3.3 ft) of the ground surface. As illustrated in the typical test boring record in Figure 1, the wide range in field standard penetration test (SPT) N-values in the Bear Bluff formation reflect the influence of cemented layers.

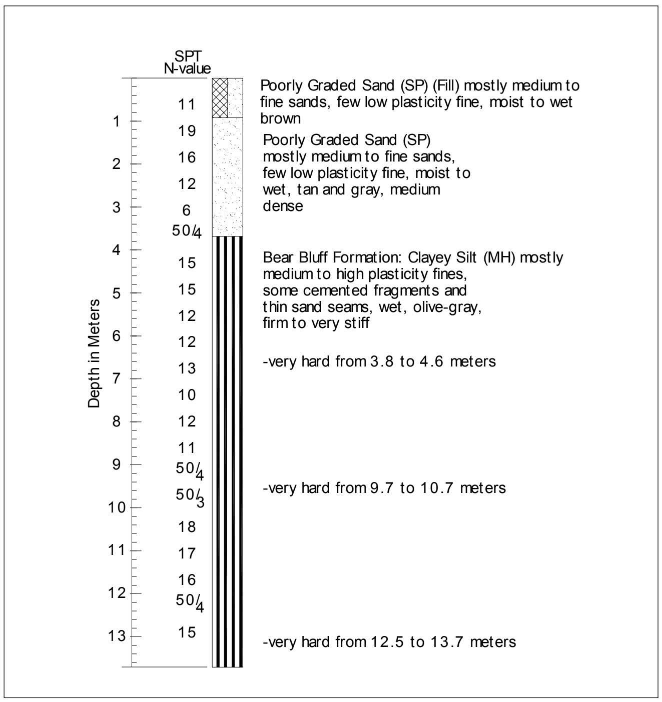

Figure 1 Typical Test Boring Record

1.3 Augered Cast-In-Place Piles

Because of the subsurface conditions and other design considerations, the oxidation ditch expansion was designed to be supported by 46 cm (18 in) diameter augered cast-in-place piles. The final design plans included over 350 piles for support of the new structure. The design axial pile capacity was determined using the contributions of both side resistance and end bearing in the Bear Bluff formation. Contribution of the overlying unconsolidated soil was conservatively ignored in determining the design axial pile capacity. The expected ultimate axial compressive capacity for the augered cast-in-place piles socketed 9.1 m (30 ft) into the Bear Bluff formation was in excess of 1600 kN (180 tons). An idealized sketch of the augered cast-in-place pile is Figure 2.

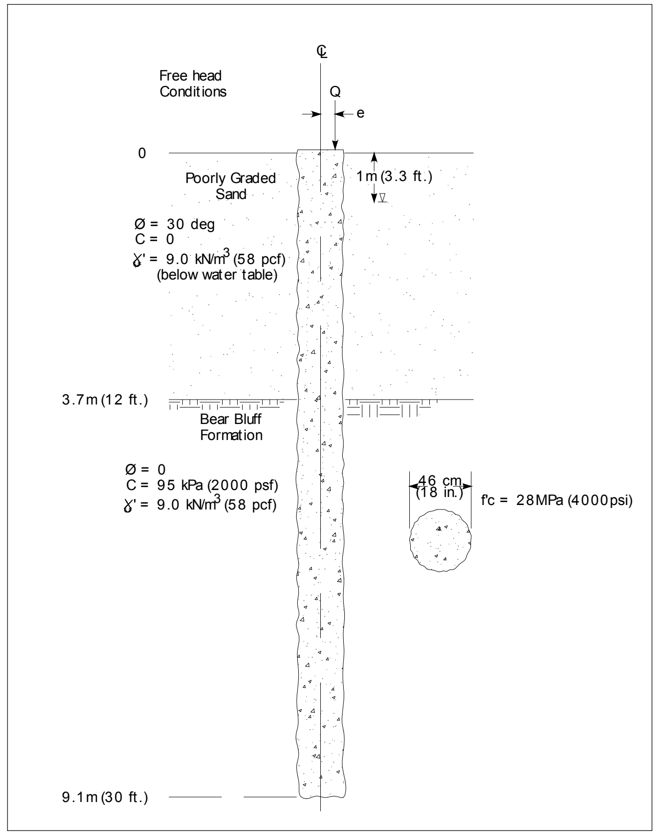

Figure 2 Idealized Sketch of Cast-In-Place Pile

From a structural perspective, the cross section of the constructed test piles was limited to hook reinforcing bars at the pile head for connection purposes. It is the authors understanding this structural detail is accepted practice for production of augered cast-in-place piles in portions of the United States and elsewhere.

2 LOAD TEST RESULTS

As described by S&ME (2002), five test piles were installed and then statically load tested in compression using the quick loading method (ASTM D1143). Test pile installation followed conventional augered cast-in-place pile construction as described by Neate (1989). In an effort to confirm the suitability of the Bear Bluff formation, the test piles were drilled to depths ranging from 9.1 m to 12.2 m (30 ft to 40 ft). Additional information on the construction of the test piles is presented in Table 1.

Table 1 Information on Test Pile Construction

Test Pile No.	Pile Depth (m)	Grout Strength (MPa)	Grout Factor
1	9.1	28.1	1.46
2	12.2	25.6	1.51
3	10.7	28.1	1.41
4	9.1	34.7	1.33
5	9.1	25.6	1.47

Note: Grout strength is 7 days after pile construction. Grout factor is actual grout volume divided by theoretical grout volume.

Graphical presentations of the compressive axial load versus vertical pile head displacement are shown in Figure 3.

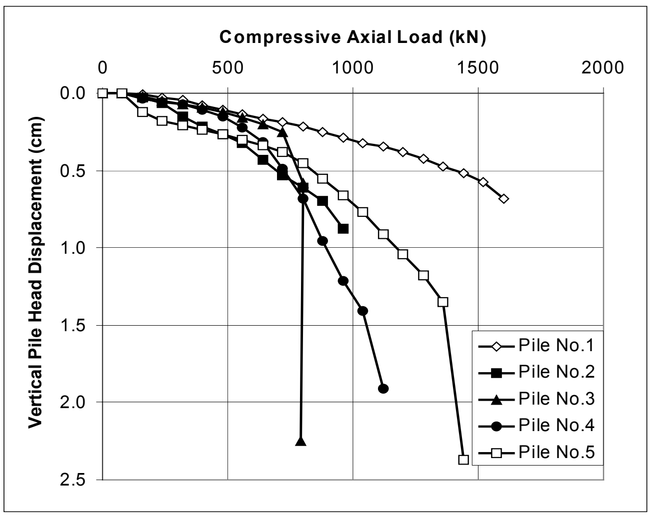

Figure 3 Load versus Pile Head Displacement

As shown in Figure 3, only Pile No. 1 could be loaded to the expected ultimate axial compressive capacity of 1600 kN (180 tons). Pile Nos. 3, 4 and 5 began to plunge at loads ranging from 800 kN to 1470 kN (90 tons to 165 tons). Testing of Pile No. 2 was terminated at a load of 960 (108 tons) because the pile head had moved laterally about 5 cm (2 in.). The compressive load test results for 4 out of 5 test piles suggested that the production piles, as designed, may not be able to achieve the minimum required factor of safety in compression.

Examination of the load test data clearly indicated that it would be necessary to determine the cause(s) of the test pile failures prior to proceeding with production pile installation. It is worthwhile to note that it was proposed by others to add to the production pile length as a solution so as not to delay construction.

3 FAILURE ANALYSIS

In the analysis following the load tests, the authors considered three possible mechanisms for the failure of the test piles. These mechanisms are: (1) overestimation of the side resistance and/or end bearing; (2) construction defects in the test piles, and/or; (3) structural limitations in the test piles. Based on a review of the data with the field engineer, testing procedural and interpretation errors were eliminated from consideration as either causing or contributing to the unsuccessful load tests.

To investigate the possible failure mechanisms, the authors proceeded with an engineering evaluation consisting of additional subsurface exploration, pile integrity testing, and numerical modeling.

3.1 Additional Subsurface Exploration

The additional subsurface exploration consisted of three test borings, one boring immediately adjacent to Test Pile Nos. 2, 3, and 5. The results of the additional subsurface exploration confirmed the results of the geotechnical characterization performed earlier in the design process.

Though it was concluded that the conditions were consistent with the design parameters, there was also the question of the appropriateness of the design parameters assigned to the Bear Bluff formation. Fortunately, several axial uplift load tests (ASTM D3224) had also been performed on other piles at the site, and their results were available. The results of the uplift load tests confirmed the design ultimate side resistance of 62 kPa (0.65 tsf) in the Bear Bluff formation. The uplift load test results also provided strong support that failures of the compression test piles were not due to overestimation of the capacity available within the Bear Bluff formation.

3.2 Pile Integrity Testing

Pile integrity testing (PIT) was performed by GRL (2002) to evaluate the condition of the test piles. The authors' concede that PIT, like other non-destructive tests, can be inconclusive, especially where piles are very long and where other conditions may be less than favorable. For this project, the PIT results provided clear evidence of anomalies indicative of pile damage. Such indications of pile damage were noticeably absent in PIT results for the three piles tested for uplift. In consideration of this, the authors concluded that the test piles were constructed in a manner consistent with the production piles, but that they were experiencing damage during load testing. A summary of the PIT results is presented in Table 2.

Table 2 Summary of PIT Results

Test Pile No.	PIT Findings
1	- Bulge from 2.4 to 4 m
2	- Pile may be broken at 1.2 m
	- Pile broken at 3.7 m
3	- Pile broken between 2.7 and 3 m
4	- Pile may be broken at 1.8 m
	- Pile broken at 5.5 m
5	- Bulge from 2.4 to 3.4 m
	- Pile broken at 3.7 m

3.3 Numerical Modeling

Although these were axially-loaded compression test piles, the intent of the numerical modelling was to investigate the shear and bending moments developed in the piles due to eccentricity. To accomplish this, the authors prepared a pile model in LPILE Plus 3.0 by Ensoft (1997). The details of the pile model and soil parmeters are shown in Figure 2. The LPILE input parameters were based on the soil conditions and the recommendations presented by Reese and Van Impe (2001). To represent the inherent eccentricity of augered cast-in-place piles, moments were applied to the model pile head along with compressive axial loads (Q) ranging from 600 kN to 1600 kN (68 tons to 108 tons, respectively).

The model pile section with negligible steel and a free-head was selected to represent the test piles. The pile deflections, shear, and bending moments estimated by LPILE are shown in Figures 4, 5 and 6, respectively. These figures indicate a substantial increase in lateral deflections, shear and bending moments with increasing eccentricity. The solid lines in these figures represent an eccentricity of 2.5 cm (1 in.) and the dashed lines represent an eccentricity of 7.5 cm (3 in.).

As shown in Figure 5, the pile damage as identified by PIT corresponds quite well to the depth of maximum shear for several of the test piles. The comparison is not as strong between pile damage and maximum moment (Figure 6). The exception is Pile No. 4, which was broken at 5.5 m (18 ft), well below both the maximum shear and bending moment predicted by the model. One explanation for this is that the LPILE model assumes that the pile section is perfectly uniform, as compared to the actual section for augered cast-in-place piles, which is expected to be irregular.

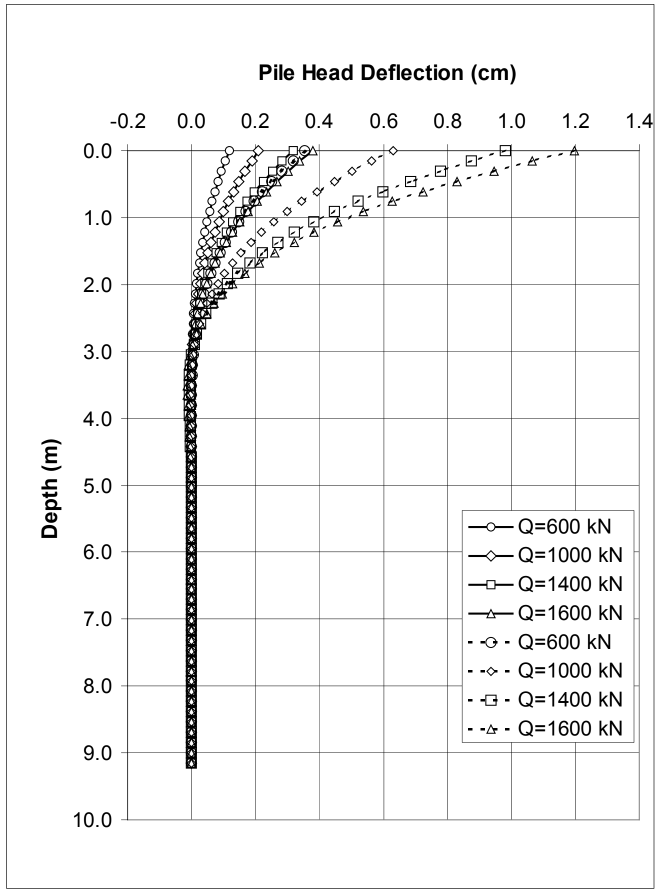

Figure 4 Lateral Deflection of Pile Model

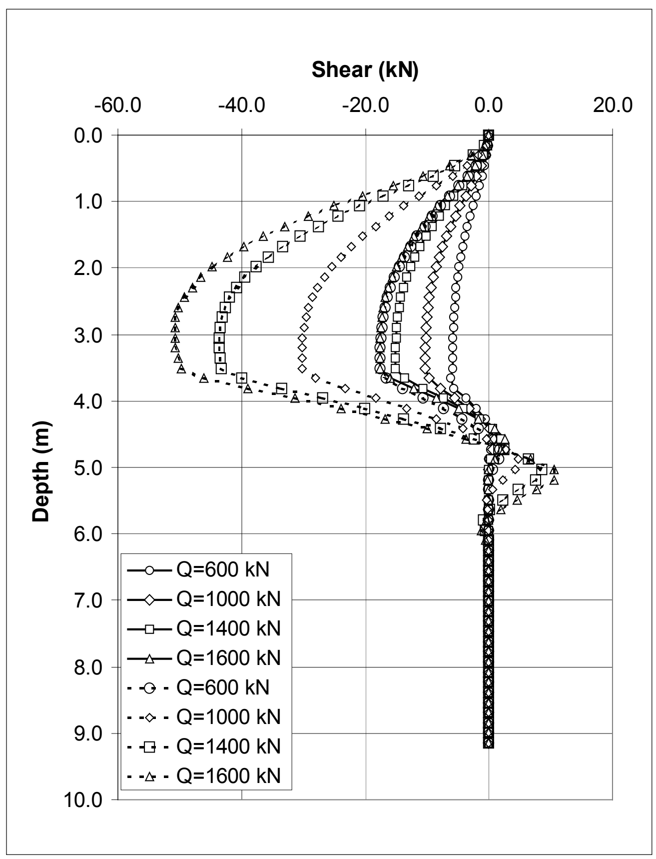

Figure 5 Shear in Pile Model

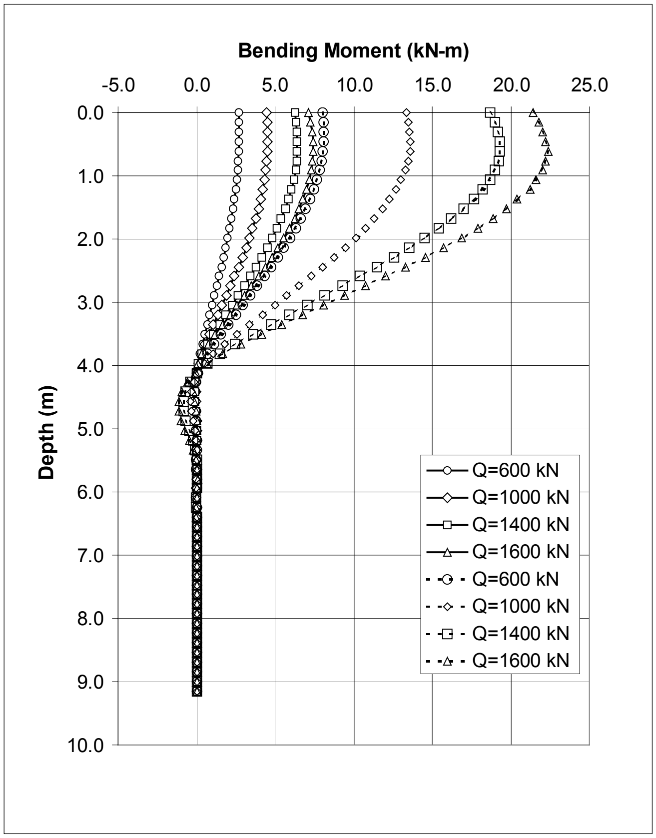

Figure 6 Bending Moment in Pile Model

3.4 Conclusions

The results of the engineering investigation support the conclusion that failure of the test piles at significantly lower than expected compressive loads was due to damage (i.e., cracking of the unreinforced pile section) incurred during load testing. The damage resulted from shear and bending moments created by eccentric loading.

While it is understood that some eccentricity is present with all pile types, the potential for eccentricity is greater for augered cast-in-place piles. Eccentricity is inherent in the augered cast-in-place construction method as it tends to create a non-uniform pile section, especially in soil conditions (e.g., loose sands and soft clays) that are favorable for the creation of bulges and other non-axisymmetrical pile conditions.

It is also concluded that there were other factors that contributed to the pile failures. One factor is the relatively lower lateral resistance that may be expected in the loose sands and soft clays in the upper portion of the subsurface profile. Another factor is the higher axial loads applied to the piles in a free-head condition during load testing. Both the higher loads and the free-head condition will intensify the effects of eccentricity.

The lessons learned from the observed pile failures described in this case history are:

- augered cast-in-place piles exhibit eccentricity that is inherent to the conventional construction method;
- high axial compressive loads applied during load testing can intensify eccentricity effects;
- augered cast-in-place piles can be vulnerable to damage from shear and moment forces, and;
- successful design and construction of augered cast-in-place piles should consider the potential for eccentric loads during load testing and during application of the superstructure loads.

Although human life was not at risk, the failure of the test piles at significantly lower than expected compressive loads represented a financial risk to the owner (i.e., the public). The failure analysis, by providing the design team with information on the mode of pile failure, helped to prevent the financial loss of additional failure and/or unnecessary change orders.

4 FINAL REMARKS

The intent of the authors in offering this case history was to help practicing engineers anticipate and thus avoid similar failures in the future. As Petroski (1994) states in his book entitled *Design Paradigms: Case Histories of Error and Judgement in Engineering,*

> "...having as wide and deep acquaintance as possible with past failures should be desirable, if not required, of all engineers engaged in design. Understanding from case histories how and why errors were made in the past cannot but help eliminate errors in future designs."

As with many projects, the test pile construction was based on past success in similar, but not identical, conditions. This may help to explain why a relatively basic principle of solid mechanics (i.e., shear and bending moments created by eccentric loads) was overlooked in constructing the test piles. Considering this, the scope of this paper may be expanded to a lesson on engineering failures, in general. The lesson, which has been described by Petroski (1982 and 1994), is that the role of the engineer is to identify failure modes for each specific project and then to design and construct to obviate failure. Concentrating only on previous successes may risk overlooking fundamental aspects of the project.

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