Research Paper

Evaluation of Tangent Bearing Element Axial Load Response

Jon Sinnreich[1]*

Abstract: Augered cast-in-place (ACIP) piles, also known as continuous flight auger (CFA) or augered pressure-grouted (AGP) piles, are a well-established method for installation of deep foundation elements. A current equipment constraint of ACIP piles is the largest practical diameter that can be constructed. To overcome this limitation, some ACIP contractors have begun offering deep foundations which in this paper will be referred to as Tangent Bearing Elements (TBEs). A TBE consists of two or more ACIP piles spaced at one diameter center-to-center. The individual pile elements form a bundle which acts as a single foundation element in axial loading. This results in an efficient foundation installation method which produces equivalent-sized elements faster than traditional large-diameter bored piles. Because of their non-traditional geometry however, design engineers may be hesitant to utilize TBEs. This paper examines the results of several bi-directional static load test programs conducted on TBEs.

Keywords: augered cast-in-place piles, continuous flight augered piles, augered pressure-grouted piles, tangent bearing elements, bi-directional static load testing

Introduction

A current equipment limitation of ACIP piles is the largest constructible diameter, which typically does not exceed 1.2 meters. In comparison, traditional bored piles can be constructed with diameters of 3 meters or greater. To offer an alternative to large-diameter bored piles, some specialist ACIP deep foundation contractors have begun offering Tangent Bearing Elements [1, 2, 3]. A TBE consists of two or more ACIP pile elements spaced at one diameter center-to-center (Figure 1). Effectively, the individual piles form a bundle which can be considered to act as a single foundation element in axial loading.

TBEs can be efficiently constructed, by having one drill rig install multiple "Number 1" elements in one day, then after 24 hours of grout curing install multiple "Number 2" elements the next day, and so on. In this fashion, TBEs are typically constructed much faster than the equivalent number of bored piles, with reported production time savings of 30% or more. Figure 2 illustrates a 12-meter deep open excavation performed to verify that individual elements will remain tangent at depth when constructing TBEs.

Because of their non-traditional geometry however, design engineers may be hesitant to utilize TBEs due to questions regarding their design and performance under load. The optimal way to assess performance is to conduct a static load test on a TBE. Bi-directional Static Load Testing (BDSLT) is an efficient type of axial load test for cast-in-place deep foundations [4, 5]. BDSLT testing has been successfully carried out on a variety of element types, including bored piles, barrettes as well as ACIP piles. It is therefore well-suited for testing TBEs, by individually installing one BDSLT sacrificial jack and ancillary equipment (collectively known as a Load Test Assembly, "LTA") into each of the individual piles comprising a TBE, to the same depth of the bi-directional fracture plane. Once the

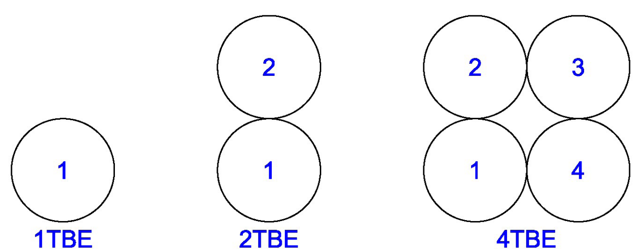

Figure 1. Tangent Bearing Element Configurations and Designation

Figure 2. Open excavation adjacent to previously cast ACIP element (courtesy Keller North America)

[1] Jon Sinnreich, GRL Engineers Inc.,
* Corresponding author, email: jsinnreich@grlengineers.com

Print ISSN: 1937-5247 Online ISSN: 1937-5255
Published by Deep Foundations Institute
Received 18 August 2023; received in revised form 24 November 2024; accepted 24 February 2024
https://doi.org/10.37308/DFIJnl.20230818.292

grout in all the pile elements satisfies minimum curing time and strength requirements, the test is conducted by pressurizing all jacks simultaneously, while monitoring all instrumentation in the TBE. This is similar to a BDSLT on a large-diameter bored pile whose load testing assembly consists of multiple jacks.

Analysis

Three case histories involving BDSLT testing of TBEs are available to the author through his personal involvement with the test programs. Each of the three programs was carried out by a different ACIP specialty drilling contractor on a different project. Each test program included a single pile element (1TBE), as well as one or more multiple-pile element (*n*TBE). Because of the commercial and competitive nature of the projects, the results have been anonymized and normalized as described below, so as not to divulge proprietary information. Fortunately, the essential performance of TBEs can be examined even under these restrictions.

The analyses presented below primarily focus on the upward load-displacement data, since this represents a single load-transfer mechanism (side shear). Downward displacement, with the exception of Case History B, would involve the separation of the load-displacement curve into a side shear and an end-bearing component for individual analysis.

Generally, the single-pile element and multi-pile elements in each project were installed in close proximity (within roughly 10 meters of each other), to the same pile base elevations, with the same reinforcement in each element and with the LTA at the same fracture-plane elevation (with the exception of Case History A, see below). This allows for a simple and direct comparison of the load capacity of the individual TBE segments above and below the LTA. With the exception of Case History A, internal forces computed from embedded strain gauges do not need to be utilized, because of the matching test element geometries.

The basic assumption made is that the side shear area and end-bearing area of a TBE is computed from the enveloping perimeter of the element. The enveloping perimeter can be thought of as the shape of an elastic band wrapped around the TBE bundle (Figure 3).

The justification is that the soils in the gaps between the individual pile are either displaced by, or admixed with, the grout overpour (typically grout is pumped into ACIP piles to 120% to 150% of theoretical volume). If the TBE layout is compact, with the individual elements clustered in a ring, the perimeter length P can be calculated as:

$$P = (\pi + n)D, \quad n > 1 \tag{1}$$

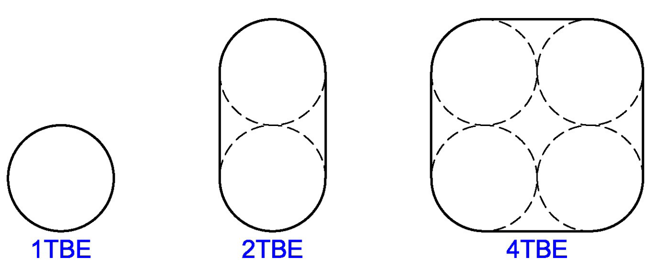

Figure 3. Enveloping Perimeter (Solid Lines)

where D is the individual pile diameter and n is the number of elements in the TBE. If the TBE is linear (elements aligned in single file), the perimeter is computed as:

$$P = (\pi + 2\,(n - 1))D \tag{2}$$

Applied loads are divided by the shear area (taken as the element length above the LTA times the perimeter area as defined above) to compute unit loads. Thes unit loads are then normalized by dividing each load by the load applied to the 1TBE element at 10 mm upward displacement.

Case History A

In this test program, a 1TBE and a 2TBE were compared. Both test foundations were constructed with 760-mm-diameter

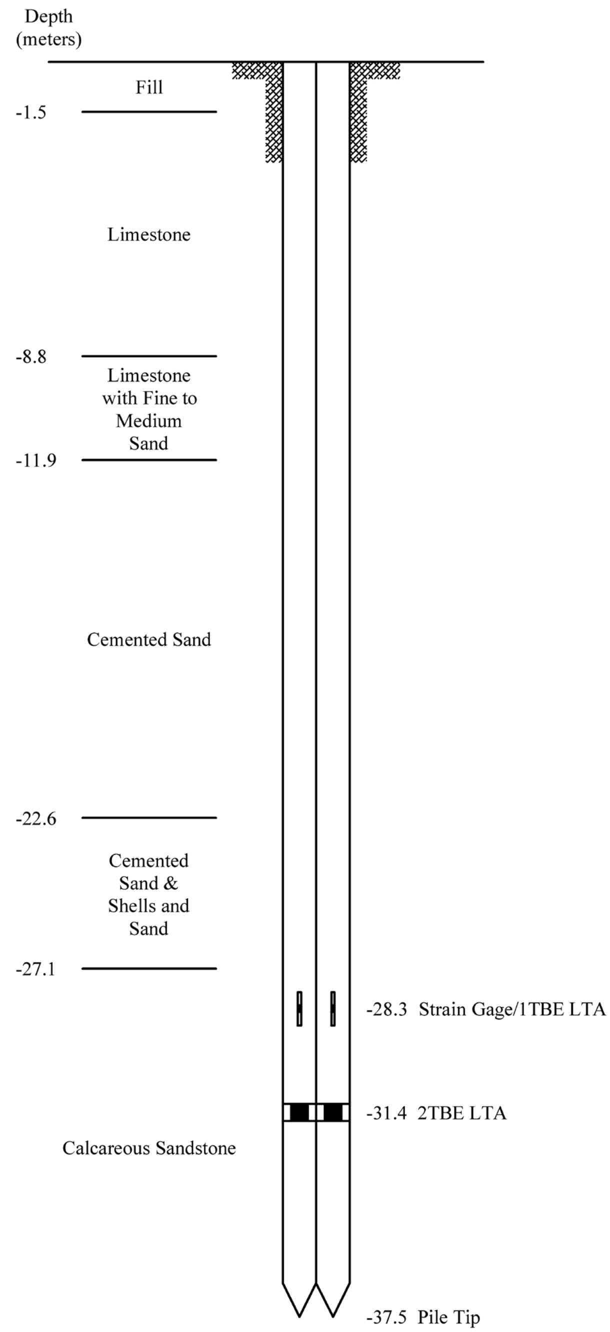

Figure 4. Elevation and Soil Profile for Case History A

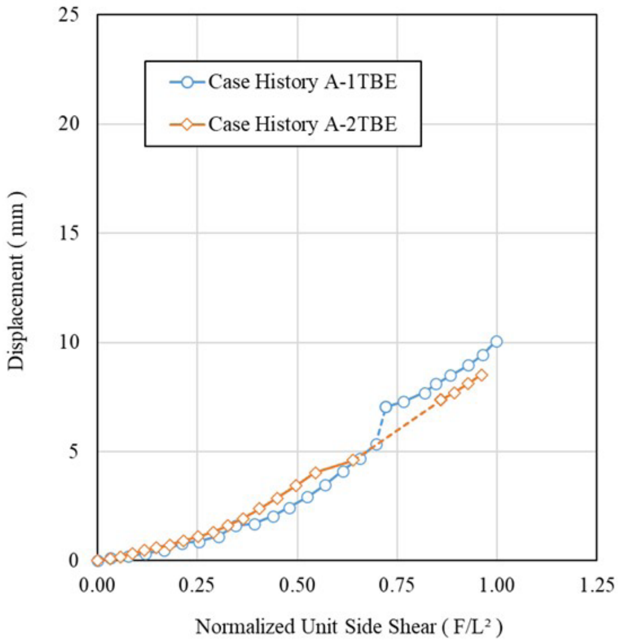

Figure 5. Upward unit side shear vs. displacement, Case History A

piles installed with a base depth below existing grade of 37.5 meters. Figure 4 illustrates the test element and generalized soil profile.

Each pile element was reinforced with a full-length rebar cage. In the 1TBE, the bi-directional LTA was installed at a depth of 28.3 meters. In the 2TBE, the LTAs were installed at a depth of 31.4 meters. However, one level of strain gages in the 2TBE was positioned at a depth of 28.3 meters, the same as the LTA in the 1TBE. Using the internal force computed at this strain gage level and the perimeter for 2TBE computed using Equation 1, the upward load and displacement data at depth 28.3 meters are converted to normalized unit side shear curves. Figure 5 plots the results. The x-axis of the plot is in units of normalized stress (force per length squared, F/L^2). The two curves show a very similar trend. The gaps in data between approximately 5 and 7 mm of displacement in both curves (indicated by dashed data series lines) are due to cycling load-unload stages, which are not recommended for any type of axial static load testing, including BDSLT, but were imposed by local building code.

The downward displacements are not compared in this case because one element of the 2TBE displaced significantly different from the other, rendering comparison to the 1TBE meaningless. This is most likely due to disturbance of the lower calcareous sandstone material during sequential installation of the two elements.

Case History B

In this test program, a 1TBE and a 4TBE were compared. Both test foundations were constructed with 610-mm-diameter piles installed with a base depth below existing grade of 30.2 meters. In both foundations the LTAs were installed at a depth of 29.3 meters, close to the pile base. Each pile element was reinforced with a single full-length centerbar. Figure 6 illustrates the test element and generalized soil profile and Figure 7 is a photo of the 4TBE test under way.

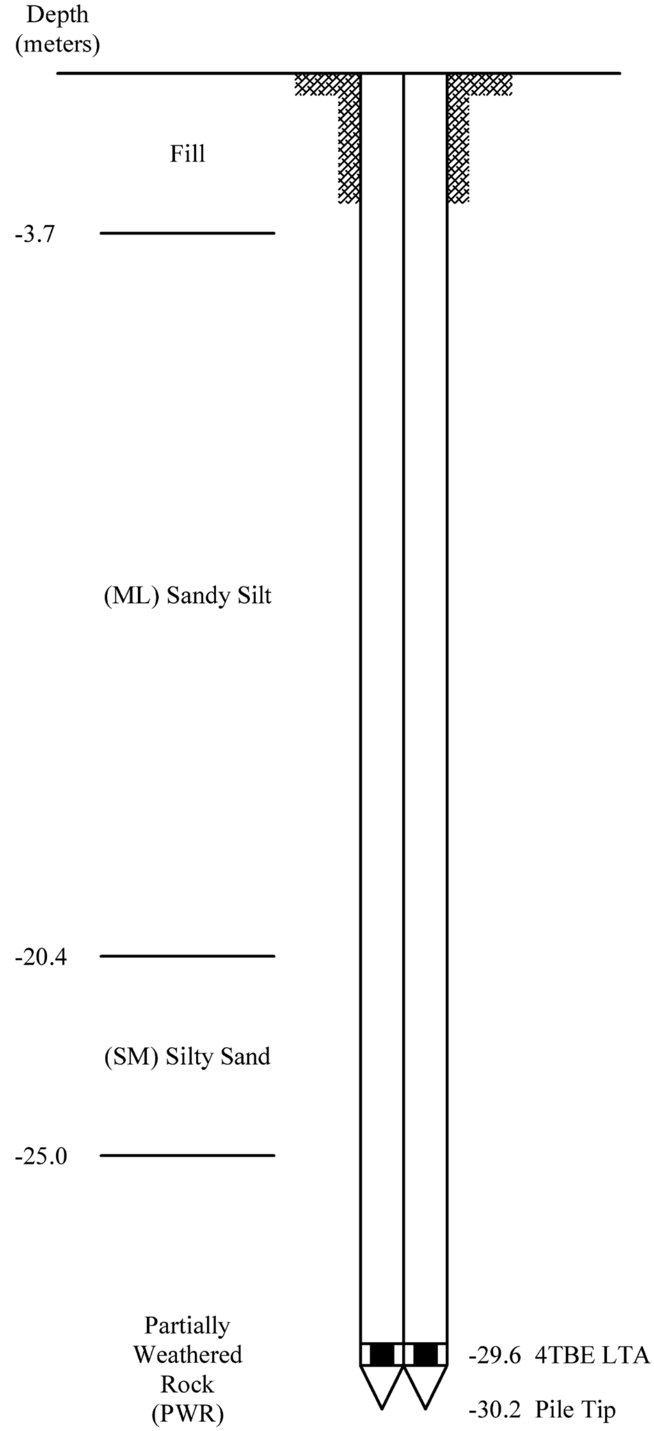

Figure 6. Elevation and Soil Profile for Case History B

Both tests resulted in relatively small upward movements and large downward movements. Because neither element achieved 10 mm of upward movement, unit shear normalization is done by fitting a Chin hyperbolic curve [6] to the 1TBE side shear data. This is accomplished by computing the least-squares parameters *m* and *b* from the unit shear and displacement data (τ and z respectively) in Equation 3 below.

$$\tau = \frac{z}{mz + b} \tag{3}$$

Figure 7. Case History B 4TBE Test Underway

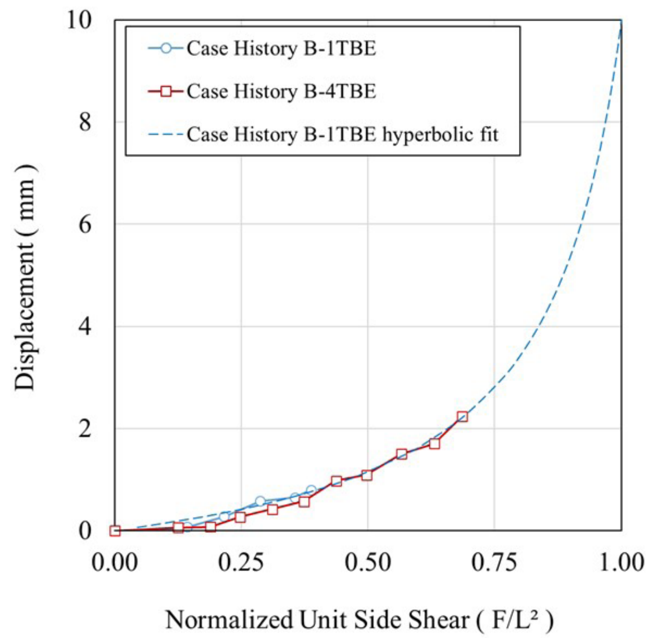

Figure 8. Upward unit side shear vs. displacement, Case History B

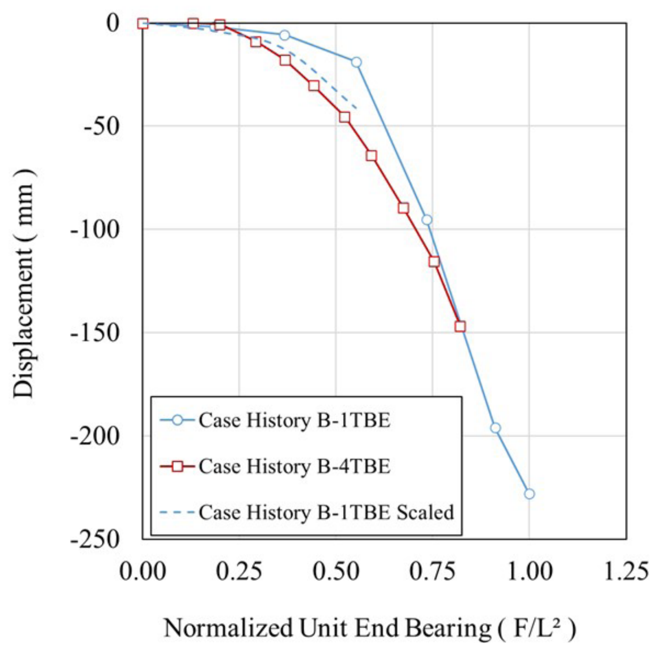

Figure 9. Unit end bearing vs. displacement, Case History B

These can then be used to compute τ at z = 10 mm. The normalized upward unit shear comparison is plotted in Figure 8, along with the Chin hyperbolic curve-fit and extrapolation computed for the 1TBE load-displacement data.

Because of the close proximity of the LTAs to the pile bases, all the applied downward load is assumed to be resisted in end bearing in this test. The unit end bearing at maximum 1TBE downward displacement (228 mm) is used as the normalizing value for the unit end bearing curves. If the end-bearing area of the 4TBE element is computed as the cross-sectional area bounded by the enveloping perimeter as defined above, the normalized unit end bearing curves, plotted in Figure 9, compare reasonably well at ultimate (plunging) displacements.

The 1TBE end bearing curve in Figure 9 is stiffer at smaller displacements. Based on the theory of elasticity [7], the settlement z of a rigid disk of diameter D subject to a uniform pressure q and fully embedded in an elastic medium which has a Young's modulus E and Poisson's ratio v is given by:

$$z = \frac{qD(3 - v - 4v^2)}{8E(1 - v)} \tag{4}$$

Although the actual end-bearing load-displacement curve is not linear elastic at any but the smallest displacements, the simple analysis given by Equation 4 suggests that for a given settlement z, an inverse relationship between D and q exists at small-strain displacements. The equivalent diameter D_{4TBE} is approximately 2.2 times the individual element diameter D_{1TBE}. That is to say, the end bearing area A_{4TBE} within the enveloping perimeter of 4TBE is equal to:

$$A_{4TBE} = \frac{\pi D^2_{4TBE}}{4} = \frac{\pi(2.2D_{1TBE})^2}{4} \tag{5}$$

Figure 9 includes a scaled load-displacement curve for the initial portion of 1TBE end bearing, in which the meas-

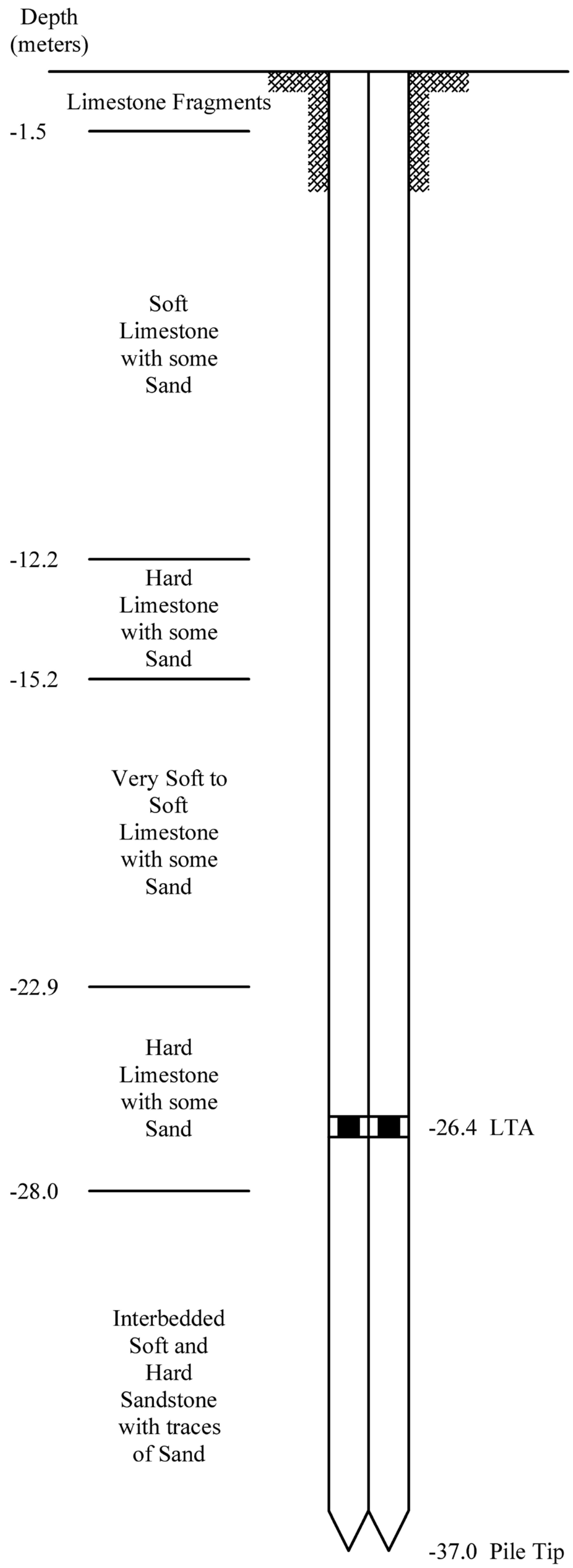

Figure 10. Elevation and Soil Profile for Case History C

Figure 11. Case History C 4TBE (foreground) and 1TBE (background)

ured displacement *z* is multiplied by the factor 2.2 (dashed line). This scaled curve appears to correspond reasonably well to the 4TBE end bearing curve below 50 mm settlement. The analysis is not extended into the fully plastic large-deformation portion of the curves since Equation 4 assumes elasticity.

Case History C

In this test program, a 1TBE, one 2TBE and one 4TBE were compared. Figure 10 illustrates the test element and generalized soil profile and Figure 11 illustrates two of the TBEs installed prior to testing.

All three test foundations were constructed with 915-mm-diameter piles installed with a base depth below existing grade of 37.0 meters. Each pile element was reinforced with a full-length rebar cage. In all three foundations the bi-directional LTAs were installed at a depth of 26.4 meters.

The magnitude of downward movement in all three tests was relatively small, and separating end bearing from side shear resistance gave inconclusive results. However, upward movement was significant. Additionally, there was also a BDSLT test carried out by the author at an adjacent lot ("Case History D", within 35 meters of the Case History C test TBEs) on a 36.2-meter-deep, 1,830-mm-diameter bored pile designated "TS3", which was drilled under polymer slurry and whose LTA was located at a depth of 29.6 meters. Although this is not an exact correspondence to the TBE configuration, it is a relatively close match, and its normalized upward unit side shear plot is compared alongside that of the TBEs in Figure 12.

All the curves show a similar trend up to a displacement of about 10 mm. Subsequently, the curves diverge. 1TBE and 2TBE maintain a similar trend, while 4TBE and TS3 indicate a relatively lower stiffness above a displacement of 10 mm. This may be due to scaling effect of larger- vs. smaller-diameter objects in the same geotechnical stratum [8], since the trend from stiffest to least-stiff also follows the sequence of smallest to largest effective diameter. It may also be caused by the procedures utilized to construct the larger elements (repeat disturbance of existing elements by the installation of the next adjacent element in 4TBE, use of

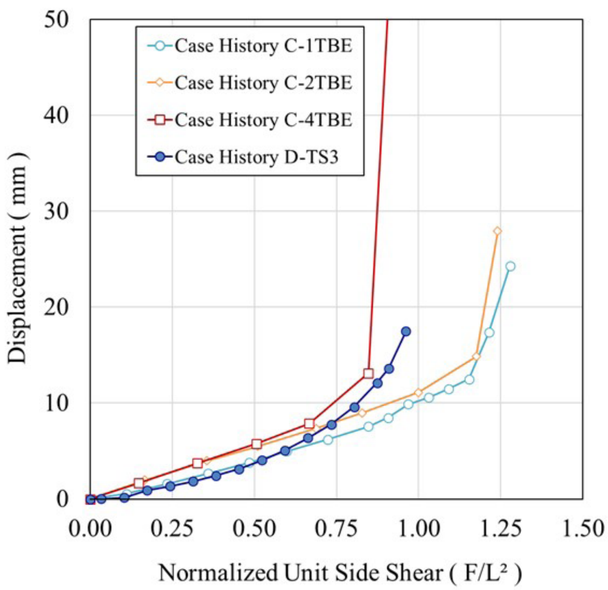

Figure 12. Upward unit side shear vs. displacement, Case Histories C and D

polymer slurry on bored pile TS3), or simply be a product of normal variability in the capacity of adjacent cast-in-place foundations.

Conclusions

Tangent Bearing Elements (TBEs) present an innovative alternative installation method which overcomes the size limitation of ACIP piles where large-diameter foundations are required. Designers and contractors may be hesitant to utilize TBEs, since their load-transfer mechanism as compared to equivalent cylindrical piles is poorly understood due to their unique geometry.

This paper presents the results of some head-to-head comparison bi-directional static load tests on TBEs. This data set, although limited, is encouraging and indicates that if a TBE's surface area is assumed to be the enveloping perimeter, the unit resistance in both shear and end bearing is comparable to a traditional ACIP pile or bored pile. Some scaling effects are apparent especially when the TBE equivalent diameter becomes large relative to the individual pile element and should be accounted for. A load test program should be part of any significant deep foundation project, and bi-directional static load testing has shown itself to be uniquely suited to verify TBEs' mobilized resistance to applied loads. The ability to verify load-bearing resistance via testing will hopefully encourage utilization of TBEs on future projects.

Potential future research efforts include the collection of additional data sets from full-scale TBE test elements for further comparison. Additionally, a numerical study should be performed using finite element modeling to validate the assumption of the enveloping perimeter as a representative shear and bearing area of a TBE configuration.

Acknowledgements

The author would like to acknowledge the trust emplaced to him by representatives of Malcolm Drilling Company, Inc., Berkel and Company Contractors and Keller North America in allowing him to share what is generally considered proprietary test results for the advancement of the state of practice of augered cast-in-place foundations.

References

1. Keller North America website: https://www.keller-na.com/expertise/techniques/tangent-bearing-elements
2. Berkel and Company Contractors website: https://www.berkelandcompany.com/deep-foundations/berkel-infinity-group-piles/
3. Malcolm Drilling Company, Inc. website: https://www.malcolmdrilling.com/services/mega-bearing-elements/
4. Osterberg, J. O., 1995. *The Osterberg Cell for load testing drilled shaft and driven piles*. Federal Highway Administration.
5. Schmertmann, J. H., Hayes, J. A., 1997. *The Osterberg Cell and bored pile testing-A symbiosis*, Proceedings of Third International Geotechnical Engineering Conference, pp. 139-166. Cairo University, Cairo Egypt.
6. Chin, F.K., 1970. *Estimation of the Ultimate Load of Piles from Tests Not Carried to Failure*. Proceedings of Second Southeast Asian Conference on Soil Engineering, Singapore City, 11-15 June 1970, pp. 81-92.
7. Davis, R.O. and Selvadurai, A.P.S., *Elasticity and Geomechanics*, Cambridge University Press, UK, 1996.
8. Sinnreich, J., 2011. *The scaling effect of bored pile radius on unit shear capacity*, International Journal of Geotechnical Engineering, 5:4, 463-467, DOI: 10.3328/IJGE.2011.05.04.463-467.

DFI Journal Underwriters

