Case Histories of Full-Scale Comparative Load Testing of Base Grouted and Ungrouted Test Shaft Pairs

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ABSTRACT: Base grouting is becoming more widely promoted in the drilled shaft industry as a means to improve shaft response to load. This paper presents several case histories of full-scale static load tests conducted on adjacent shafts with and without base grouting on projects in various parts of the United States. All tests were performed by Loadtest USA using the Osterberg Cell (O-cell) test method. The comparisons yielded some intriguing results. In some cases the results matched theory quite well and showed improvement to stiffness and/or overall capacity. In other circumstances this was not the case. These case histories illustrate the need for further load testing and research to better understand how drilled shaft capacity is affected by base grouting, particularly how the capacity is affected by drilling, base cleaning and base grouting techniques and quality control in various soil materials.

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INTRODUCTION

Post-construction base grouting (or tip grouting) of deep foundation elements, typically drilled shafts (bored piles), is becoming more common in the United States. Although the practice of base grouting is not new, its rising popularity has led many, including the authors, to ponder whether the state of knowledge is keeping up with application. There is a limited amount of direct comparisons between grouted and ungrouted shaft performance available in the literature (Dapp & Mullins 2002 and Dapp & Brown 2010 are the only two examples found by the authors).

In the past ten years Loadtest USA has performed bi-directional load tests on a variety of projects where base grouting was performed. On several projects, multiple shafts were tested, with and without base grouting. Most of these "comparison shafts" were the same diameter, and in the one instance where this was not true, the authors applied analytical techniques to compute equivalent capacities. All comparison shaft pairs were tipped in similar material. Case studies of these projects and specifically the comparison shaft pairs are presented herein. It is neither the authors' intention to present a comprehensive study on this complex subject nor to come to specific detailed conclusions. Rather, it is to present a sample of test results which indicates the wide array of possible outcomes when employing base grouting to "improve" drilled shafts.

BACKGROUND

Loadtest USA specializes in bi-directional axial compressive load testing using O-cell technology. A common test configuration consists of an O-cell at or near the base of a drilled shaft. The test shaft is concreted in a similar fashion to production drilled shafts. The O-cell is encased and surrounded by concrete (see Figure 1). Instrumentation is embedded around the O-cell to measure expansion. Strain gages are often installed at various depths within the drilled shaft to measure strain and ultimately compute load at different depths.

When the concrete is sufficiently hardened the test is performed. The O-cell is pressurized until the concrete around the cell is fractured and the O-cell is immediately unloaded. The two shaft components above and below the O-cell are now free to move with only the shaft's reaction to resist the movement. Movement curves are then generated relating applied load to upward and downward displacement. Load is derived by relating the pressure to the O-cell's calibration curve.

The top of shaft movement is monitored with high precision digital survey levels. The shaft compression is measured using traditional telltales. The upward top of O-cell movement is computed by adding compression and top of shaft movement. The downward movement is calculated by subtracting the expansion from the upward top of O-cell movement. T-Z (unit shear) curves can also be generated if strain gages are installed.

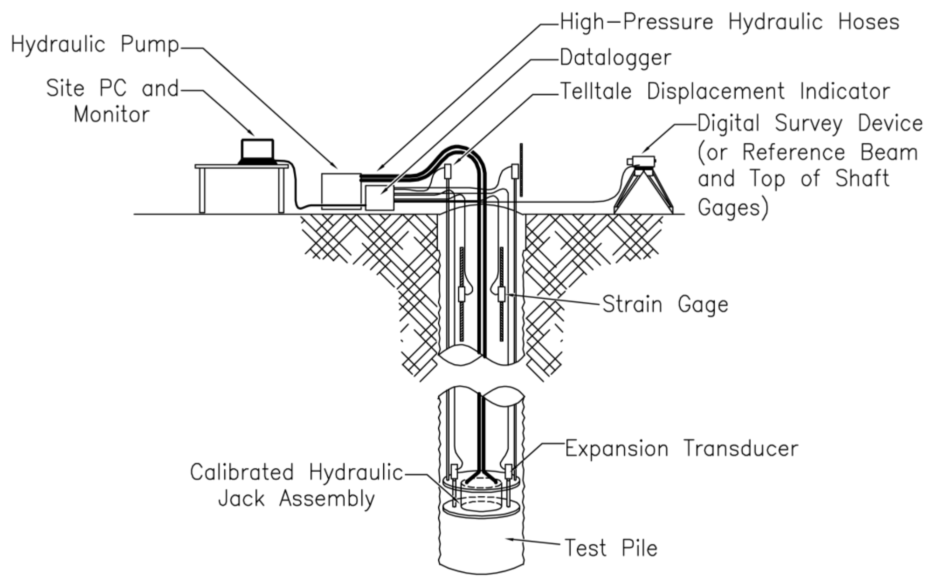

Fig. 1. Schematic representation of an O-cell test shaft

Finally, a unit end bearing curve is generated. The accuracy of this curve depends on how close to the tip of shaft the O-cell is and how well known the unit shear is between the O-cell and shaft tip. For all the case studies presented herein, the accuracy of unit end bearing is considered to be high, since the O-cells are close to the tip and strain gages were employed to evaluate the unit shear near the O-cell.

A typical base grouting apparatus and O-cell test assembly installed in the rebar cage is pictured in Figure 2.

Fig. 2. Typical base grouting apparatus installed at the cage tip.

The apparatus consists of several sets of tube-a-manchette pipes in a “U” configuration, with a supply line and return line each, enclosed in a cover plate. Similar apparatus was used in all of the case studies presented herein.

CASE STUDIES

1. Sandy River Bridge

Location: Troutdale, OR

General Contractor: Hamilton Construction

Drilling Contractor: Malcolm Drilling

The Oregon Department of Transportation (ODOT) is replacing the aging Interstate 84 bridges over the Sandy River with two new steel box girder bridges. The original plan was base grout all shafts, and to test three shafts using the Osterberg Cell method. During construction it was decided that one shaft could be tested without base grouting (see Figure 3 for test results).

Each test assembly consisted of three O-cells on a single level. Test Shaft 1 (TS-1) was not base grouted, while shafts TS-2 and TS-3 were base grouted. The contractor used a 2,490-mm (98-inch) O.D. temporary sectional oscillator casing which was advanced with an oscillator to shaft tip, and a clamshell grab to excavate and clean the shaft bottom under water. For the base grouted shaft the grouting occurred a few days after concreting. All three test shafts were approximately 36.6 meters (120 feet) deep and tipped in dense sand.

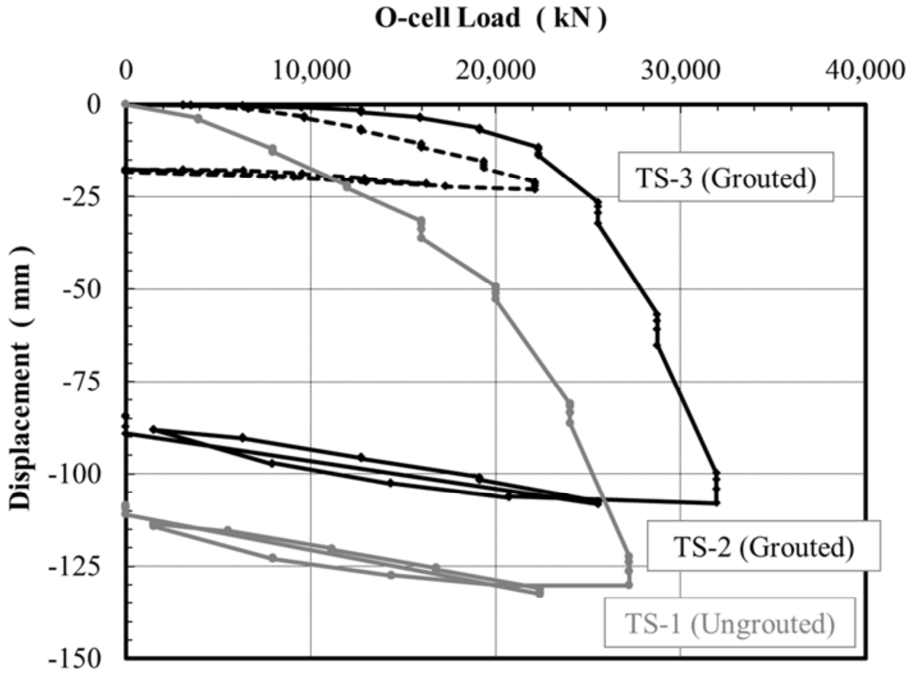

Fig. 3. Downward O-cell Load-Displacement Curves for Sandy River Bridge

The results of TS-1 served to confirm the engineering design assumptions. TS-2 and TS-3 showed an improved stiffness response but TS-2 only showed a small improvement to the ultimate capacity. The TS-3 load test was halted at a relatively small downward displacement in order to limit shear displacement of the production shaft above the O-cells. Table 1 lists the unit end bearing vs. displacements of each of the three shafts, as derived from the O-cell tests.

Table 1. Sandy River Bridge unit end bearing data.

TS-1 (ungrouted) Bent 2EB North		TS-2 (base grouted "a") Bent 4EB South		TS-3 (base grouted "b") Pier 2 South	
Displ. (mm)	Unit EB (kPa)	Displ. (mm)	Unit EB (kPa)	Displ. (mm)	Unit EB (kPa)
0.0	0	0.0	0	0.0	0
4.1	108	0.3	75	0.3	71
12.7	216	0.5	152	1.3	143
22.6	328	0.8	230	3.8	220
36.1	439	2.3	313	7.1	293
52.8	548	3.6	395	11.7	367
86.1	663	6.9	480	17.3	443
130.3	754	14.0	567	23.1	502
		32.3	656		
		65.3	747		
		108.0	842		

2. Broadway Viaduct

Location: Council Bluffs, Iowa

Drilling Contractor: Longfellow Drilling

The current Broadway Viaduct bridge was originally built in 1955, and currently carries well over 30,000 vehicles daily. Optimizing the design of the new bridge required addressing several project constraints, including the existence of nearby historic structures and the numerous streets and railroad tracks that run under the bridge, which rendered pile driving undesirable. Four piers with base grouted drilled shafts were proposed as the foundation solution. Subsurface conditions at the two test shaft locations were very similar and consisted primarily of sands and silty clay. Longfellow Drilling constructed the two 22.9-meter (75-foot) deep, 1,525-mm (60-inch) diameter dedicated drilled test shafts under polymer slurry. The shafts were tipped into fine to coarse sand. The base of each shaft was cleaned using a cleanout bucket. Applied Foundation Testing (AFT) performed base grouting on one of the two shafts.

Each test shaft was equipped with a single O-cell installed at a depth of 18.3 meters (60 feet). Loadtest USA then conducted O-cell load testing on both 1,525-mm (60-inch) shafts in order to compare the load response of the conventional drilled shaft to the base grouted drilled shaft. Figure 4 plots the downward displacement vs. load for both the grouted and ungrouted shafts, and reveals some interesting features. While some increase in capacity for the grouted shaft (TS-2) did occur at the service limit state, the displacement increased rapidly after 5,000 kN (1,100 kips); much more so than for the ungrouted shaft (TS-1). Further, the ultimate capacity seemed to be higher in the ungrouted shaft. Table 2 lists the calculated unit end bearing vs. displacements of each of the two shafts, as derived from the O-cell tests.

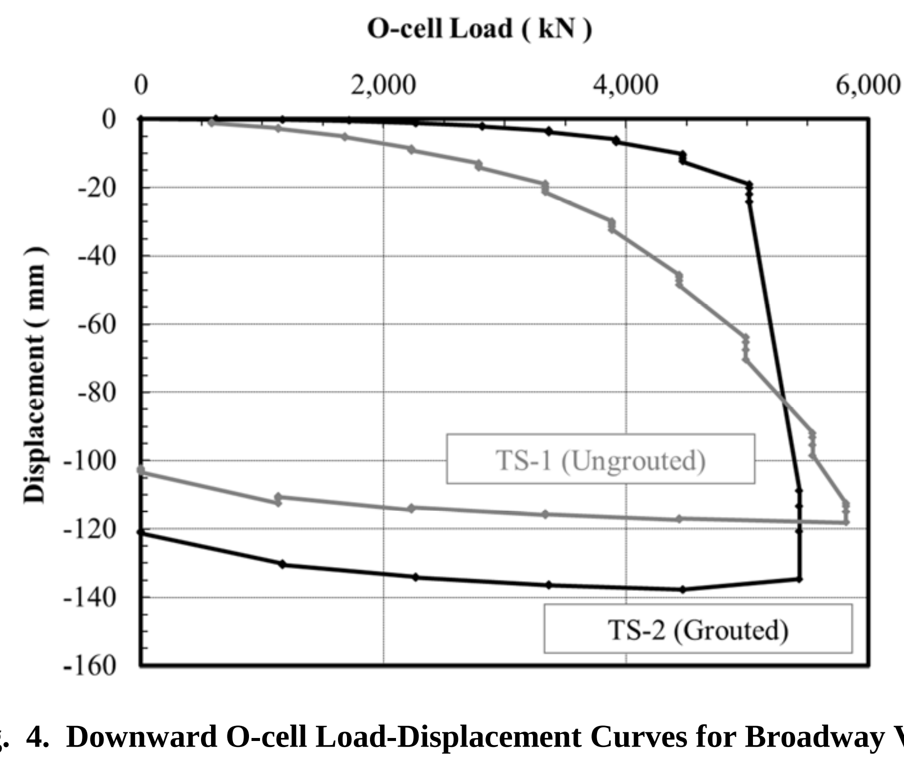

Fig. 4. Downward O-cell Load-Displacement Curves for Broadway Viaduct

Table 2. Broadway Viaduct unit end bearing data.

TS-1 (ungrouted)		TS-2 (base grouted)	
Displ. (mm)	**Unit EB (kPa)**	**Displ. (mm)**	**Unit EB (kPa)**
0.0	0	0.0	0
1.0	8	0.0	4
2.8	20	0.3	8
5.3	32	0.5	21
9.1	44	1.3	44
14.2	58	2.3	62
21.3	80	3.8	86
32.5	110	6.9	107
48.5	153	12.4	128
70.4	201	24.4	146
98.6	248	134.6	259
118.1	274		

3. <u>Wisconsin Zoo Interchange</u>

Location: Milwaukee, WI

Client: CH2M Hill

Drilling Contractor: Malcolm Drilling

The Zoo Interchange, which originally opened in 1963, is Wisconsin's oldest and busiest interchange, combining three major freeways and carrying over 300,000 vehicles daily. The enormous undertaking of its reconstruction is a task that prompted WisDOT to seek numerous design alternatives. Loadtest USA assisted in the testing program to optimize foundation design for structures of the Zoo Interchange.

Three pairs of dedicated tests shafts, ranging in diameter from 1,220 mm (48 inches) to 2,490 mm (98 inches), were installed, with one of each pair base grouted. All shafts were outfitted with a single O-cell (see Figure 5 for typical O-cell and base grout assembly). The primary objective was to validate design assumptions based on pressure-meter testing (PMT) at each pair. Since base-grouting methods have been purported to substantially increase the shaft and base resistance in drilled shafts, the secondary objective was to compare and determine the potential improvement of the shaft and base resistance due to base grouting. Results from two of the three pairs are analyzed in the next section (the third pair of tests did not yield data useful to the analysis).

Fig. 5. O-cell and tube-a-manchette system in rebar cage

Sub-surface conditions consisted primarily of loose silt and soft clay underlain by medium to very stiff clay with trace gravel. The shafts were constructed under water by advancing segments of oscillated casing into the ground and removing the soil inside with an auger. The casing was advanced in this manner to the tip of the shaft and removed during concrete placement.

Results of the testing program indicated that the base resistance was greater in all of the base grouted drilled shafts, which allowed for higher design values. Furthermore, since shafts of different diameters were tested, the results provided flexibility in optimizing the foundation design for a complex series of bridges and structures for this project. Tables 3a and 3b list the computed unit end bearing vs. displacements of the 1,980-mm (78-inch) diameter and 2,490-mm (98-inch) diameter test shaft pairs, respectively, as derived from the O-cell tests.

Table 3a. Zoo Interchange 1,980-mm diameter shaft unit end bearing data.

WTS-1 (ungrouted)		WTS-2 (base grouted "a")	
Displ. (mm)	Unit EB (kPa)	Displ. (mm)	Unit EB (kPa)
0.0	0	0.0	0
3.3	126	0.3	131
4.8	154	0.8	256
6.4	184	1.8	295
8.6	217	3.3	338
		4.8	385
		6.9	432
		9.7	479
		13.2	529
		17.0	577
		20.8	594

Table 3b. Zoo Interchange 2,490-mm diameter shaft unit end bearing data.

CTS-1 (ungrouted)		**CTS-2 (base grouted "b")**	
Displ. (mm)	**Unit EB (kPa)**	**Displ. (mm)**	**Unit EB (kPa)**
0.0	0	0.0	0
0.8	34	0.3	57
1.8	69	1.0	123
2.5	105	2.3	163
3.6	137	4.1	204
9.9	161	8.1	245
18.5	194	18.8	285
29.0	230	32.3	327
46.0	268	54.6	367
56.6	308	70.9	408
75.2	348	95.0	447
		109.0	473

4. Missouri DOT Research Project

Location: Frankford and Warrensburg, MO

Client: University of Missouri

The Missouri DOT (MoDOT) and the University of Missouri undertook an ambitious project to develop improved drilled shaft design parameters and procedures. As part of the field testing aspect of this project, Loadtest USA performed testing at two different test sites in Missouri that were chosen to reflect the potential range of ground conditions where base grouting is likely to be effective. Subsurface conditions at the Frankford test site consisted of low variability, with very weak shale overlying competent shale. In contrast, the Warrensburg site was chosen for its irregularity, with 4.6 meters (15 feet) of overburden overlying thick, highly variable shale. A total of 25 test shafts were constructed at the two sites in Frankford and Warrensburg, MO. At each site the contractors were able to drill the shafts in the dry with very limited use of casings. The Warrensburg site included five base grouted shafts to help determine any potential improvement in shaft performance and to determine the reliability of any improvement that may be realized. The results of this project are used in a MoDOT report that includes recommendations for the proper use of base grouted drilled shafts, as well as a means to verify specific design methods (see Loehr et. al., 2011). Two Warrensburg test shafts, one grouted and one ungrouted, were selected to add to this case history survey, based on similar location, depth, diameter, construction technique and mobilized downward displacements.

Both 915-mm (36-inch) diameter test shafts were roughly 9.1 meters (30 feet) deep. They were cased to top of shale which was roughly 4.6 meters (15 feet) deep. TS-W6 was grouted and TS-W2 was not. The shafts were drilled with an auger and core barrel and the base was cleaned with an auger. The downward load displacement plots for each shaft are presented in Figure 6. Table 4 lists the calculated unit end bearing vs. displacements of both shafts.

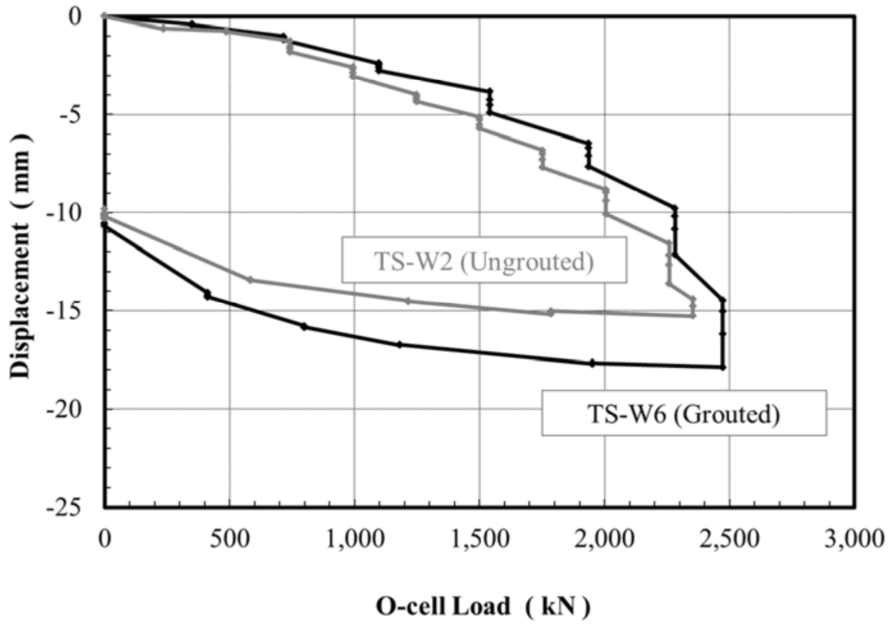

Fig. 6. Downward O-cell Load-Displacement Curves for Missouri Research Project

Table 4. Missouri DOT Research Project shaft unit end bearing data.

TS-W2 (ungrouted)		**TS-W6 (base grouted)**	
Displ. (mm)	**Unit EB (kPa)**	**Displ. (mm)**	**Unit EB (kPa)**
0.0	0	0.0	0
0.5	37	0.5	49
0.8	87	1.3	110
1.8	128	2.8	174
3.0	173	4.8	256
4.3	220	7.6	329
5.6	269	12.2	396
7.6	317	17.8	432
10.2	367		
13.7	416		
15.2	434		

5. <u>John James Audubon Bridge Project</u>

Location: St. Francisville, LA

Drilling/General Contractor: Audubon Bridge Constructors (Flatiron Construction, Granite Construction and Parsons Transportation Group JV)

Owner: Louisiana DOTD

The John James Audubon Bridge is a roadway span over the Mississippi River in south central Louisiana. Famed artist and naturalist John James Audubon painted 32 of the works in his Birds of America series while residing at Oakley Plantation in nearby St. Francisville. The new bridge was named after John James Audubon to honor his contribution to the documentation and preservation of the rich natural history of the region. The bridge consists of cable-stayed main span and replaces a ferry between the communities of New Roads and St. Francisville. The bridge conveys Louisiana Highway 10. The total bridge length, including the main span and approach spans, is 3.9 km (2.4 miles). The main span, at 482.5 meters (1,583 feet) length, is currently the second-longest cable-stayed bridge in the Western hemisphere.

Each of the two main piers is supported on 21 drilled shafts in a 3 x 7 grouping. The 1,980-mm (78-inch) diameter shafts were approximately 61 meters (200 feet) deep, embedded in alluvial deposits primarily consisting of sands and gravels. The shafts were constructed by first installing a permanent casing with a vibro-hammer, then using a full-depth temporary segmented casing which was oscillated in advance of the excavation. Material inside the casing was removed using a grab, or by water-jet and airlift, depending on the soil conditions. The base of each shaft was airlifted and visually inspected using a Shaft Inspection Device (SID). Dapp and Brown (2010) give a full description of the project, as well as results of their analysis of all the test shafts.

All but one of the test shafts (T-3 at Pier 1W) were base-grouted. The grouting apparatus consisted of tube-a-manchette system under a base plate. Each shaft was tested using an assembly of four individual O-cells welded in a horizontal array between two bearing plates, positioned several feet above the shaft base grouting system. For inclusion in this overview, the adjacent test shafts (T-1, T-2 and T-4) of Pier 1W are compared to T-3.

The downward load-displacement curves recorded at each of the four test shafts in the group are plotted in Figure 7. Table 5 lists the calculated unit end bearing vs. displacements of each of the four test shafts at Pier 1W, as derived from the O-cell tests.

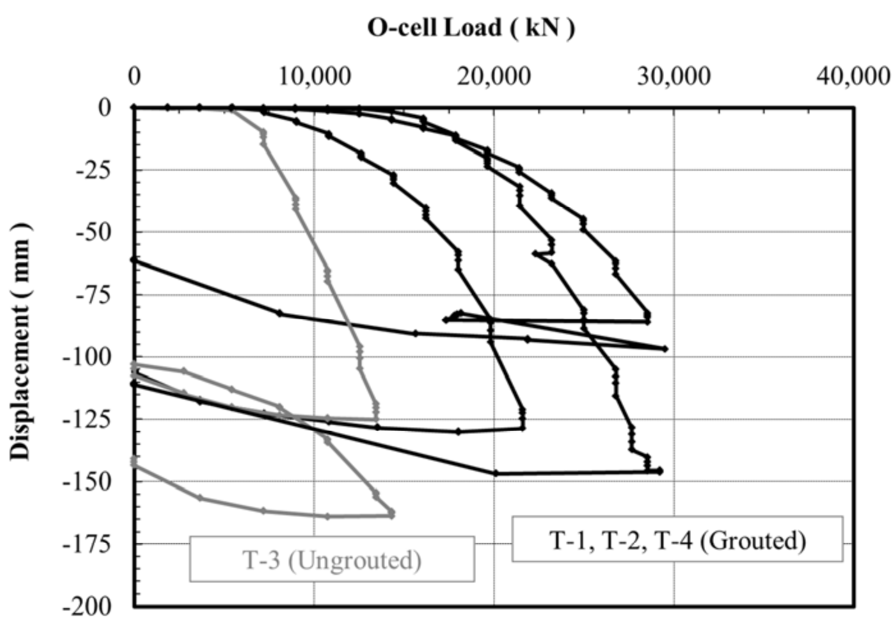

Fig. 7. Downward O-cell Load-Displacement Curves for Audubon Bridge Pier 1W Test Shafts

Table 5. Audubon Bridge Pier 1W shaft unit end bearing data.

T-3 (ungrouted)		T-2 (base grouted "a")		T-4 (base grouted "b")		T-1 (base grouted "c")	
Displ. (mm)	Unit EB (kPa)	Displ. (mm)	Unit EB (kPa)	Displ. (mm)	Unit EB (kPa)	Displ. (mm)	Unit EB (kPa)
0.0	0	0.0	0	0.0	0	0.0	0
0.3	60	0.3	53	0.1	28	0.1	63
1.0	99	0.5	172	0.2	89	0.2	127
15.0	151	0.8	233	0.3	149	0.3	152
40.9	214	1.3	294	0.4	204	2.3	210
69.6	276	2.5	354	0.5	266	6.1	239
104.9	339	5.1	410	0.6	328	11.4	290
125.0	370	8.6	463	1.5	388	20.1	350
		12.4	519	5.8	438	30.2	410
		18.3	575	13.2	488	44.5	470
		25.9	632	23.6	545	65.0	530
		36.3	693	39.6	607	94.0	591
		49.0	756	62.7	669	128.8	651
		66.8	818	88.6	732		
		86.1	880	115.6	794		
				137.2	825		
				145.8	857		

ANALYSIS

In each of the case histories presented in the previous section, two or more adjacent test shafts were constructed, one shaft which was not base grouted and the other(s) which was (were) grouted. Unit end bearing data was derived for every test shaft by computing the shear component of the shaft section below the O-cell using strain gage data, and subtracting it from the applied O-cell load. In order to compare all of the results presented herein, not just of each set of matched test shafts but from all five projects, all of the unit end bearing curves are normalized in the following manner:

First, a hyperbolic curve-fit to the unit end-bearing data is applied in order to smooth out the data (see Fleming 1992 for a discussion of the hyperbolic curve-fitting method). The form of the hyperbolic curve-fit function is given by Equation 1:

$$\mathbf{w}/\mathbf{q} = \beta_1 \mathbf{w} + \beta_2 \qquad (1)$$

where **w** and **q** are the displacement and unit end bearing and the terms β_1 and β_2 are constants which are determined using the least-squares method.

Second, the hyperbolic function is extrapolated in order to estimate the ultimate unit end bearing capacity, defined here as the asymptote of the hyperbolic function:

$$\mathbf{q_{ULT} = 1/\beta_1} \tag{2}$$

Third, for each paired data set, both unit end bearing capacities are normalized to the ungrouted shaft's ultimate end bearing capacity $\mathbf{q_{ULT}}$. Fourth, for each paired data set, displacements **w** are normalized by dividing by the computed displacement at $\mathbf{q = 0.5q_{ULT}}$ (so that the normalized displacement equals 1.0 at one half of the asymptotic ultimate). The net result of this normalization is that all of the ungrouted end bearing vs. displacements plot on the same curve (see Figure 8). The thick black line represents all five ungrouted unit end bearing curves. The base grouted end bearing vs. displacement curves are also plotted on Figure 8, each normalized using the parameters of its corresponding ungrouted shaft, in order to visualize the relative change in unit end bearing performance after grouting. Plots are labeled according to the case history numbers.

In all the case histories discussed herein, the pressure was not maintained in the grout lines after the completion of grouting. Therefore the shaft is loaded and unloaded by the grouting operation, then re-loaded when tested using the O-cell. As in any multi-cycle load test, subsequent load-displacement curves are stiffer than the initial curve, but only up to the previous maximum load (generated by the maximum grouting pressure, in this case). This probably accounts for at least some of the observed stiffness increase in all of the grouted test shafts relative to the ungrouted shafts in the initial portion of Figure 8. It is also possible that the effective shaft end area increased in some cases. In computing unit end bearing using nominal base area, this could lead to inflated unit values.

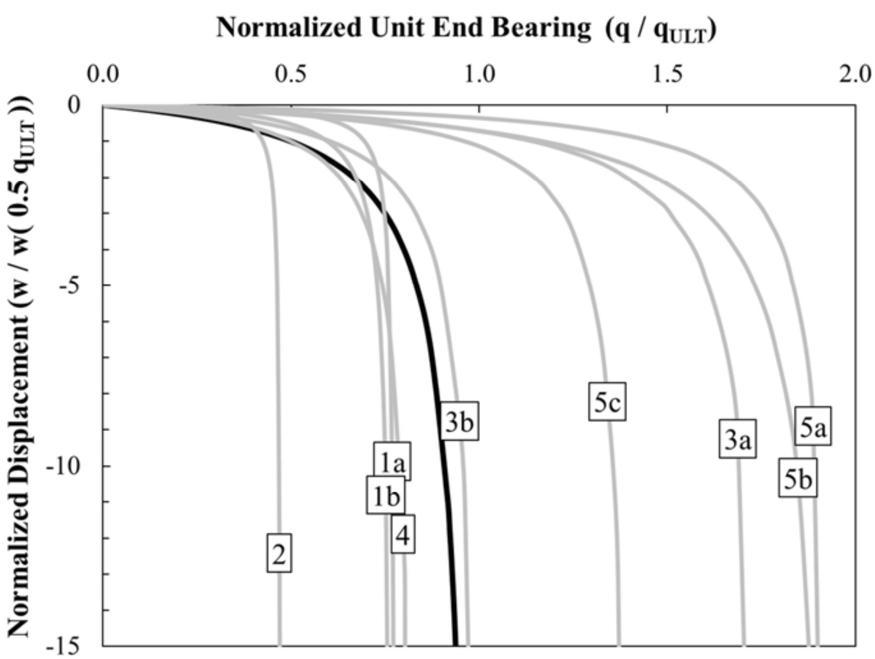

Fig. 8. Normalized Displacements vs. Unit End Bearing (numbered plots correspond to case history numbers)

CONCLUSION

Post-construction shaft base grouting is becoming common in many deep foundation projects. This paper presents five case histories, including a total of nine grouted and five ungrouted shafts, which cover a large spectrum of typical construction techniques, grouting procedures and geographic areas. In each project discussed herein, one set of adjacent shafts of equivalent diameter and tipped in similar material were constructed. One or more shaft(s) of each set was base grouted, while one was not. Each shaft was then tested using the O-cell method, and the resulting unit end-bearing curves compared. In order to assess the impact of base grouting, all of the results were curve-fit in order to estimate ultimate end bearing capacity and then normalized in such a way that all of the ungrouted unit end bearing data plotted on essentially the same curve. This allows for an assessment of the relative impact of grouting on all of the tested shafts, independent of actual total settlements or capacities.

In all instances, it appears that the initial bearing stiffness was improved by base grouting. In four grouted shafts, it appears that base grouting did not affect the ultimate capacity significantly (possibly within normal variation of shaft construction). This result correlates well with the analysis of Fleming 1993, which postulated that pre-stressing of the shaft base does not increase the ultimate capacity, but only changes the shape of the load-displacement curve. In another four shafts (the Zoo Interchange grouted shaft and the three Audubon Bridge grouted shafts), the base grouted ultimate capacity increased significantly, and in one shaft (Broadway Viaduct), the base grouted ultimate capacity *decreased* significantly. No obvious correlation to soil materials, construction technique or grouting procedure was discerned by the authors. It may be concluded that further research into the mechanics of post-construction base grouting and its impact on shaft capacity is needed, coupled with systematic testing of drilled shafts, both grouted and ungrouted, in order to more fully understand the utility of base grouting and how its successful application can be assessed and measured.

There are many factors besides grouting that can affect the end bearing load response of a drilled shaft, including disturbed bottom, heave, soil material type at the base and below the base, use and treatment of drilling fluid and base cleaning method. The authors acknowledge that these factors may explain some of the inconclusive results presented herein. All drilled shaft projects stand to benefit from rigorous quality assurance techniques and well-defined acceptance criteria for every aspect of shaft construction, to mitigate construction-related variability which may negate any benefit derived from base grouting.

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