Post-Grouting of Drilled Shaft Tips on the Sutong Bridge: A Case History

Dr. Osama Safaqah[1], P.E., Robert Bittner[2], P.E. & Xigang Zhang[3]

[1] Project Manager, Ben C. Gerwick, Inc., 20 California Street, San Francisco, CA 94111
[2] President, Ben C. Gerwick, Inc., 20 California Street, San Francisco, CA 94111, U.S.A
[3] Design Manager, Highway Planning and Design Institute, Peoples Republic of China.

ABSTRACT

The Sutong Bridge across the lower Yangtze River in China will have, when completed, the longest span (1,088 m) and the highest towers (306 m) of any cable stayed bridge in the world. The foundations for this record-setting span are drilled shafts under each of the main pylons. The North Pylon is supported on 131 drilled shafts, 2.5 m diameter and 114 m long. The South Pylon is supported on 131 drilled shafts 2.5 m in diameter and 117 m long. The tips of all drilled shafts were post-grouted after an extensive test program confirmed significant increase in capacity with post-grouting. This paper presents a description of the post-grouting test program, the results obtained, and the construction methods used for post grouting of the production drilled shafts.

Introduction

Drilled shaft design methods have traditionally relied on mobilizing skin friction along the shaft length to resist service axial loads. End bearing, if not discounted, is usually significantly reduced and mainly employed to satisfy extreme load conditions or safety factor requirements. This is mainly due to the concept of strain incompatibility since ultimate end bearing is mobilized at a shaft displacement two or three orders of magnitudes larger than the displacement required to mobilize ultimate skin friction. This is especially true for larger diameter shafts. Moreover, the displacement needed to mobilize significant end bearing is likely to be larger than estimated due to drilling-induced soil disturbance at the tip of the shaft and debris remaining after cleanout. As a result, developments in drilled shaft construction technology have been mainly focused on increasing shaft diameter or shaft length in order to increase shaft axial capacity. Increasing shaft axial capacity reduces the required number of substructure units which serves to reduce the overall foundation cost, especially in difficult construction environments.

An effective alternate technique that can be used to increase shaft axial capacity is post-grouting of drilled shaft tips. This technique, although introduced four decades ago, has not been widely used in the US despite its significant potential for cost saving and improvement of quality control of drilled shaft construction. This technique works by effectively preloading and densifying the soil and any remaining debris under the tip of the shaft by pressure grout delivered by a system of pipes pre-attached to the reinforcement cage of the shaft. As a result, larger end bearing capacity can be mobilized at the tolerable displacement limit, thus increasing overall shaft capacity without having to increase its length or diameter.

This paper introduces a case history in which post-grouting of drilled shaft tips has been successfully used to increase the axial capacity of the pylon foundation shafts of the Sutong River Bridge.

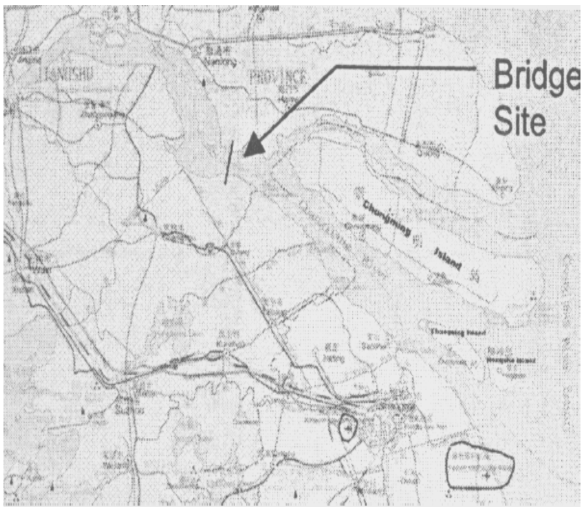

Figure 1 Sutong River Bridge Site

Figure 2 Sutong Bridge Main Span

The Sutong Bridge crosses the lower Yangtze River in China, as shown in Figure 1. It will have the longest span (1,088 m) and highest tower height (306 m) of any cable stayed bridge in the world. The signature main span of the bridge is shown in Figure 2. Detailed design of the bridge was performed by the Design Group of Sutong Project, while construction management is performed by the Jiangsu Provincial Sutong Bridge Construction Commanding Department (CCD). COWI, and Ben C. Gerwick, Inc. served as special consultants to CCD during design and construction of the bridge.

The width of the Yangtze River at the bridge site is 6 km. The site conditions at the main bridge towers are extremely challenging. The northern and southern pylons, Piers 4 and 5 are located in about 30 and 16 m of water depth, respectively. Maximum wave heights can exceed 3.5 m, and the velocity of the river currents can exceed 3.0 m/sec due to high fresh water runoff volumes and tidal effects.

Drilled Shaft Foundation Design and Construction

The foundation of each A-shaped pylon consists of 131 2.5 m-diameter drilled shafts. As shown in Figures 3, the shafts are capped by a 13 m deep dumbbell-shaped pile cap with plan dimensions of 113.8 m by 48.1 m. The drilled shafts have 2.8 m-diameter 25 mm-thick permanent steel casings that extend from elevation -7.0 m to elevation -53.0 m. The bottom of the cap tremie seal is positioned at elevation -10 m, approximately 12.0 m below mean sea level. The design tip elevation of the northern and southern pylon shafts are -124 m and -121 m, respectively.

A steel platform 3.0 m above high water level was constructed over the pier site for the construction of the drilled shafts along with an upstream mooring platform and a downstream batch plant platform. The main platform was used as a template to drive the 131 drilled shaft permanent steel casings and to provide a work deck for drilling units. A combination of vibratory and diesel impact hammers was used to drive the steel casings, while drilling was performed by eight rotary drill units. Hole stability was maintained using bentonite slurry. The reinforcement cages were fabricated in four sections. The cages were later assembled together over the top of the steel casing using threaded mechanical connectors. A central tremie pipe was used to place concrete in the drilled hole. The concrete was supplied by the batch plant, with a capacity of 100 m^3/hr, positioned on the downstream platform.

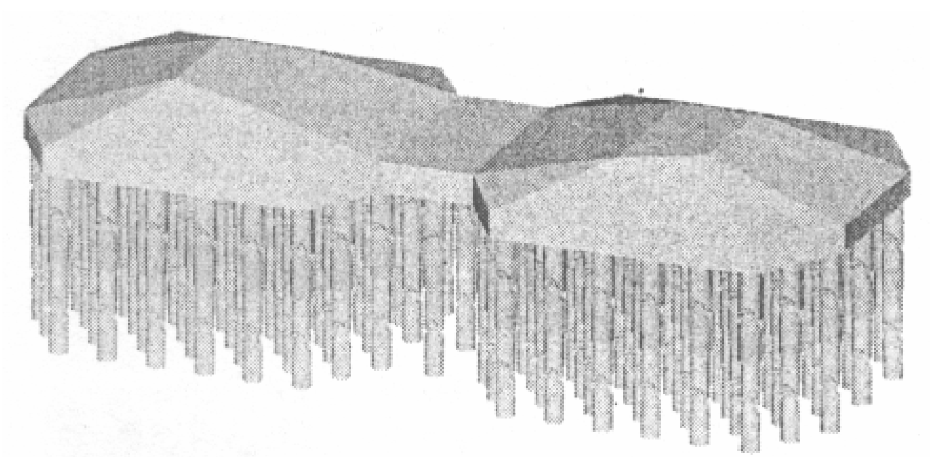

Figure 3 Sutong Bridge Pylon Foundation

Drilled Shaft Axial Capacity

The maximum demand axial shaft load was determined to be 44.0 MN for the pylon foundation. With an adopted design safety factor of 2.0, the design axial load capacity of the pylon shaft should therefore be at least 88.0 MN.

The Chinese codes which applied to this project determine the ultimate axial capacity of the drilled shaft as the minimum of: 1) the load at which the shaft settlement is 80 mm, 2) the load at which creep is 0.2 mm per hour at the end of 24 hr load application, and 3) the load at which there is a dramatic and sudden change in the load versus displacement curve.

The soils at the pylon site consist mainly of firm to stiff CL clay extending to elevation -45 m followed by layers of medium to very dense fine to coarse sands and silty sands with occasional loam layers. Bedrock is located at approximately 240 m below riverbed. Based on the soil conditions, and the estimated skin friction of a 2.5 m diameter shaft, the design team decided that a shaft tip elevation of -124 m at the northern pylon and -121 m at the southern pylon would be sufficient if a significant percentage of end bearing could be relied on. To achieve this while meeting the settlement and creep criteria, and to minimize the detrimental impact of drilling-induced soil disturbance and remaining debris at the bottom of the drilled hole, post-grouting of the shaft tips was selected as the most economical solution. Also, a 2.8 m diameter permanent steel casing was selected to extend to an average elevation of -53 m to maintain hole stability and to increase lateral stiffness of the foundation in the upper clay layers.

Post-Grouting of Shaft Tips

Post-grouting of drilled shaft tips is usually conducted using two techniques; the flat jack, or the sleeve-port (also called tube-a-manchette). In the first technique, grout is delivered by tubes attached to the rebar cage to a steel plate with a rubber membrane underneath at the tip of the shaft. In the second technique, which was used in this project, grout is delivered to the tip through loop-shaped pipes which are pre-attached to the rebar cage. For this project, six tubes were used. The bottom of each pipe, at the tip of the shaft, has a U-shape and extends approximately 50 cm into the interior of the shaft, as shown in Figure 4. Grout was discharged through eight holes 8 mm in diameter in the underside of each U-shaped pipe, which was encased by a bicycle tire to act as a tight fitting rubber sleeve creating a one-way valve. The advantage of this system is that it allows clean water to be pumped under pressure to ensure that the system is not plugged during concrete placement operations, and confirms that an open access to the shaft tip area is maintained.

The major issues in post-grouting of shaft tips, other than the design of the grout delivery system, are to determine the grout pressure and grout quantity. The work of Mullins et al (2006) shows that the level of grout pressure is the most important factor affecting the gain in end bearing and the stiffness in its load-displacement relationship. Another secondary factor is the time period of application of grout pressure. In this project, grouting operations have been controlled by both grout quantity and grout pressure. The project criteria require the grout pressure to reach the targeted level for at least five minutes, and the gout quantity to be at least 80% of the design value. Obviously, since grout pressure acting on the shaft tip is resisted by the shaft skin friction, the maximum grout pressure, and therefore the maximum achievable enhancement in end bearing, is governed by the ultimate skin friction resistance. This also means that the process of post-grouting of shaft tips will cause an upward movement in the shaft as the soil-shaft interface is strained. Therefore, field measurements of the uplift movement of the top of the shaft when related to the applied grout pressure can provide valuable information to verify the axial capacity of production shafts. For the Sutong Bridge, the skin friction of the pylon shafts was estimated as 64 MN; therefore, for a 2.5 m diameter shaft, the estimated maximum grout pressure that can be applied at the shaft tip was 13 MPa plus the buoyant weight of the shaft. Practically, a lower grout pressure was used since the maximum pressure that can be applied in the field was 7 MPa.

Figure 4 U-shaped grouting pipes at the shaft tip

In addition to the upper limit governed by ultimate skin friction, the grout pressure should exceed the hydrostatic pressure at the shaft tip. The project criteria adopted the following method to determine the minimum operating pump pressure:

$$P_g = P_w + \xi \sum_i \gamma_i L_i \qquad (1)$$

where P_g and P_w are the pump and hydrostatic pressures at the shaft tip level, respectively, and γ_i and L_i are the effective unit weight and thickness of each layer (i) above the shaft tip, respectively. ζ is an empirical coefficient for grout resistance, which is a function of the type of soil material at the shaft tip. For sands, ζ ranges from 1.5 to 3.0. Therefore, the estimated minimum operating grout pump pressure in this project was 3 MPa.

Based on the estimated upper and lower grout pressure limits and the required gain in end bearing to meet the design safety factor, the design team decided to use a grout pressure of 5 MPa, which was subject to verification by field tests. Although not used during the design phase of this project, one can estimate the gain in end bearing as a function of the applied grout pressure and shaft settlement using the recent work of Mullins et al (2006), which suggests the following equation:

$$TCM = 0.713(GPI)(\%D^{0.364}) + \frac{\%D}{0.4(\%D) + 3.0} \quad (2)$$

where %D is the shaft settlement as a percentage of its diameter D, TCM (tip capacity multiplier) is the ratio between the end bearing at a %D settlement to the end bearing at a settlement equal to 5% shaft diameter. GPI (grout pressure index) is the ratio of the applied grout pressure to the ungrouted end bearing at a settlement of 5%D. The ungrouted end bearing at a settlement of 5%D was estimated as 3.5 MPa for the pylon shafts. Therefore, for an applied grout pressure of 5 MPa, i.e. GPI of 1.43, the estimated TCM from this approach for 1%D, 3%D, and 5%D settlement is 1.3, 2.2, and 2.8, which correspond to an allowable end bearing capacity of 4.6, 7.7, and 9.8 MPa, respectively. Therefore, if this approach was used during the design phase of the project it would also indicate that a 5 MPa grout pressure would be sufficient to obtain at least 25 MN in end bearing while meeting the project settlement requirement of 80 mm. The design end bearing of 25 MPa was the end bearing targeted to obtain an ultimate axial shaft capacity with safety factor of 2.0.

The design grout quantity was estimated as 100 kN based on the porosity and grout penetration ratio of the soil at the shaft tip. Consideration was also given to the grout going upward around the pile shaft.

O-Cell Tests with Post-Grouting of Shaft Tips

To measure and verify the skin friction and end bearing capacities of the design shafts, several on-shore and offshore shafts were tested. The results presented herein are from an O-cell test on an offshore shaft constructed at the southern pylon site which was loaded before and after grouting.

The 2.5 m diameter test shaft had a tip elevation of -121 m with a 2.8 m diameter 25 mm thick permanent steel casing with a tip elevation of -53 m, as shown in Figure 5. Six U-shaped grout pipes were attached to the shaft reinforcement cage as shown in Figure 4. O-cells were placed at two levels. The upper level was 28 m above the shaft tip with two 870 mm diameter O-cells and a total nominal ultimate load of 55 MN, while the lower level was 1.5 m above the shaft tip with two 660 mm diameter O-cells and a total nominal ultimate load of 32 MN. Four LVWDTs (Linear Vibrating Wire Displacement Transducers) were installed at each O-Cell level. Eight levels of vibrating wire strain gauges and four telltales were used as shown in Figure 5. The test was conducted by LOADTEST Singapore office. The soil profile at the test site consists of layers of gray silty CL clay down to elevation – 53.5 m overlying layers of fine to coarse sands that extend well below the shaft tip elevation.

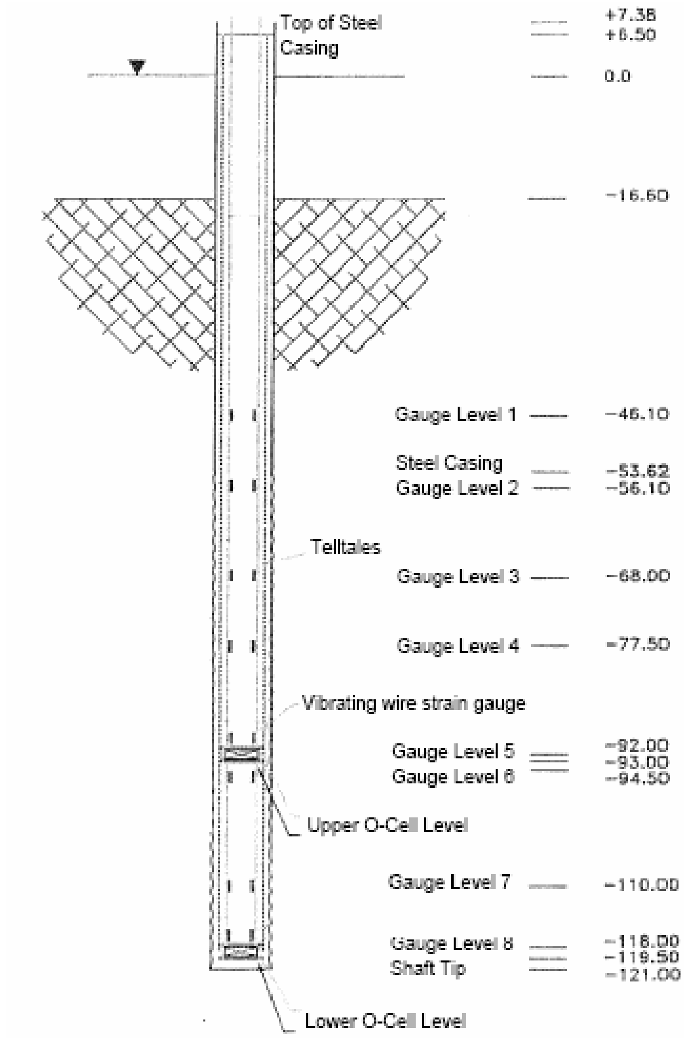

Figure 5 Test shaft layout and instrumentation

The test was conducted in two phases; before and after grouting of the shaft tip. The first phase was commenced on November 7, 2003, and consisted of a one-stage load test. In this phase the lower O-cells were pressurized in 17 loading increments, each 0.9 to 1.0 MN and lasting 30 minutes, while the upper O-cells were kept closed. As shown in Figure 6 and summarized in Table 1, at the end of the 17th increment, the total lower O-cells load was about 16.5 MN with a total expansion of 93 mm, mostly from end bearing settlement, which is larger than the 80 mm limit required by the project design criteria. At the end of the first phase tests, the shaft was unloaded in 5 increments.

The second phase of the test was conducted 5 days after grouting of the shaft tip. The grouting process was conducted in three cycles to help achieve a uniform treatment of the soil at the shaft tip. In each cycle, the grout pressure was increased in equal increments to the design level, while the grout quantity was distributed equally in the straight grout pipes. In the first cycle 50% of the neat cement grout quantity was extruded, followed by pressure washing the grout pipes with clear water. After at least 1.5 hours of waiting, 30% of the grout quantity was extruded after which the grout pipes were pressure washed again with water. After at least 3.5 hours of waiting, the third cycle was completed by extruding the remaining 20% of the grout quantity. In the first and second cycles, there was more emphasis on controlling the grout quantity, while in the third cycle more emphasis was put on controlling the grout pressure.

Two main stages of load tests were conducted in the second phase. In the first stage the lower level O-cells were pressurized in 28 loading increments, each 0.9 to 1.0 MN, while the upper level O-cells were kept closed to assess the improvement in end bearing after grouting. As shown in Figure 7, after the final loading increment, an end bearing load of 27 MN was achieved with 44 mm tip settlement (1.8%D), while for a 1%D settlement, the measured end bearing capacity after shaft tip grouting was 5.3 MPa, which agrees well with the value predicted by the Mullins et al (2006) approach. This level of gain in end bearing was satisfactory and showed that the process of post-grouting of shaft tips can be reliably depended on to obtain the required design axial load capacity of the shafts while meeting the project settlement limit and eliminating the risk associated with drilling-induced soil disturbance and remaining debris at the tip of the shaft.

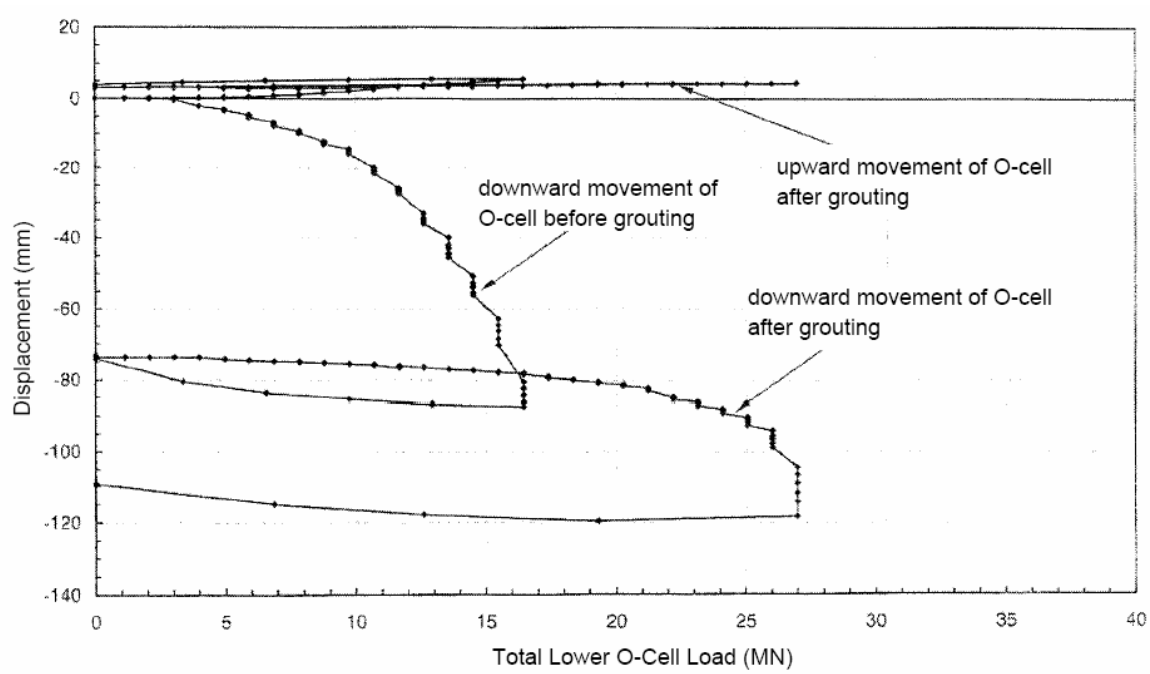

Figure 6 Load-displacement curves before and after post-grouting of shaft tip from Stage 1

To measure the skin friction response along the shaft after grouting, a second stage of loading was conducted as part of the second phase of the test. This time, the upper level O-cells were pressurized in 1.6 to 1.7 MN load increments while the lower level O-cells were unlocked. The test was stopped when the upper shaft segment ultimate skin friction was reached after moving 106 mm upward, but before reaching the ultimate skin friction of the lower segment, as shown in Figure 7. From this test, it can also be noticed that the lower 28 m long shaft segment close to grouted tip has a much stiffer skin friction load-displacement response than the upper 77 m segment. This is also evident from the load distribution curves based on strain gauges measurements, shown in Figure 8.

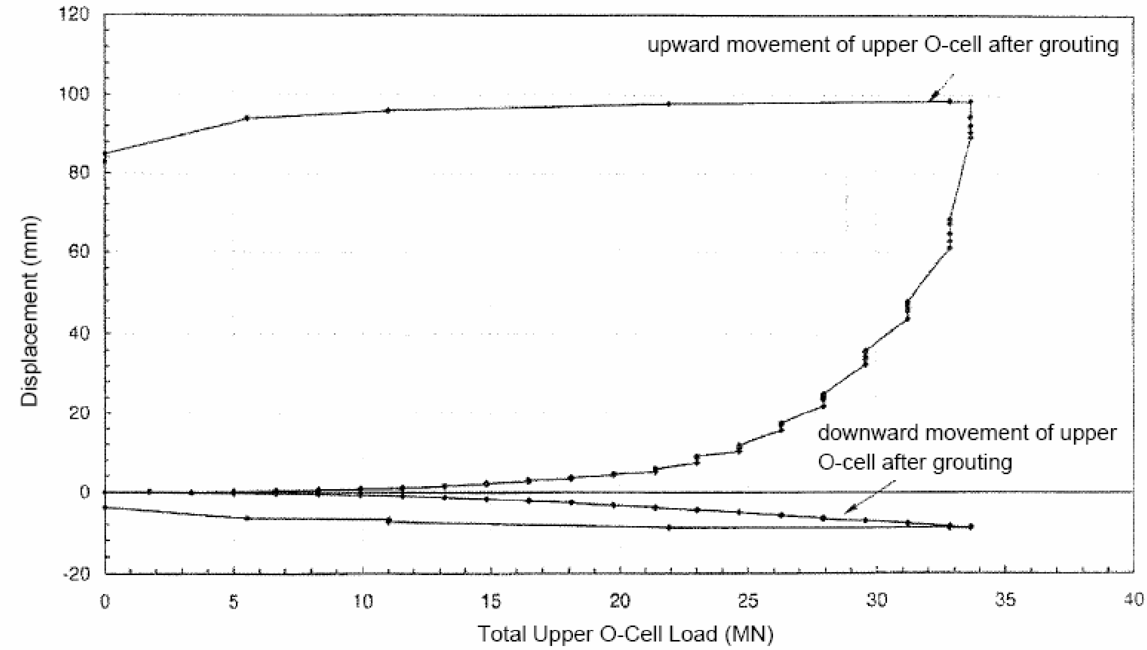

Figure 7 Load-displacement curves after post-grouting of shaft tip from Stage 2

Table 1 A summary of O-cell tests procedure and results before and after grouting

Stage		Loading Level	Upper Level O-Cells			Lower Level O-Cells		
			Max Load (MN)	O-cell Hydraulic System	Total Expansion (mm)	Max Load (MN)	O-cell Hydraulic System	Total Expansion (mm)
Before Grouting		1L-1 to 1L-17	0	Closed	-1.7	16.5	Pressure	+93.0
After Grouting	1	2L-1 to 2L-28	0	Closed	-1.4	27.0	Pressure	+118.5
	2	3L-1 to 3L-21	33.7	Pressure	+106.0	0	Free	+113.7

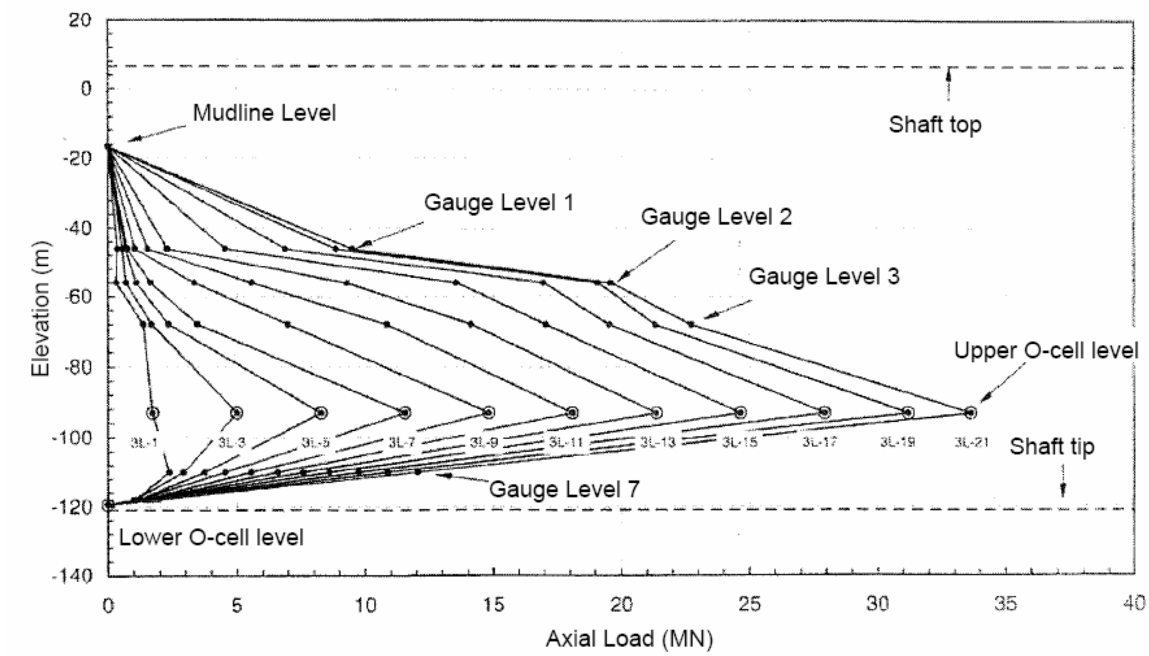

Figure 8 Shaft load distribution curve from stage 2 using strain gauge data

Conclusions

Post-grouting of shaft tips is an effective and economical procedure that was implemented to increase the axial capacity of the drilled shaft foundation of the Sutong Bridge in China. By preloading and compaction of the soil and any remaining debris at the shaft tips, the end bearing capacity can be significantly increased and reliably depended on. This was validated in O-cell tests conducted on shafts before and after tip grouting. Another advantage of post-grouting of shaft tips is the ability to check the axial capacity of each production shaft through measurement of grout pressure and upward movement of the top of the shaft.

References

Bittner, B. R., Zhang, X., Jensen, O. J., Thoegersen, K., and Hansen, O. R. (2005). “Design and construction of the Sutong Bridge foundation,” proceedings of the 2nd DFI Marine Foundation Specialty Seminar, New York.

Mullins, G., Winters, D., and Dapp, S. (2006). “Predicting end bearing capacity of post-grouted drilled shaft in cohesionless soils,” ASCE-GI Journal of Geotechnical and Geoenvironmental Engineering, 132 (4), 478-487.