

TECHNICAL AND ECONOMIC BENEFITS OF O-CELL LOAD TESTING FOR DEEP FOUNDATIONS IN INDIA

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ABSTRACT: This paper describes the Osterberg Cell (O-cell) test method used for the static axial compressive load testing of bored piles and discusses its advantages over traditional top-down testing. The O-cell test uniquely separates side shear from end bearing, using one as reaction to test the other with the possible loading far exceeding top-down tests. A properly designed test that includes appropriate instrumentation should fully mobilize both the end bearing and the side resistance, as well as define the depth profile of side shear resistance. Analysis of the test result provides an equivalent top-load curve for design based on the measured response of the separate components of capacity. The results from ten O-cell tests conducted on full-scale, large-diameter, high-capacity, bored test piles of three different projects in Mumbai region are presented. The O-cell test can provide a useful tool for optimizing foundation design, which can result in significant economic savings.

INTRODUCTION

The Osterberg cell (O-cell) load test [1] is a bi-directional, axial, compressive, static load test conducted on deep foundations to evaluate the soil-pile resistance. Dr. Jorj Osterberg developed this testing technique in 1987, and subsequently helped to start the company Loadtest, founded in 1991. Since then, more than 3,000 O-cell tests have been conducted around the world including the 206 MN load world record test. Schmertmann and Hayes [2] describe some of the many technical and economic advantages for the O-cell test, which are also discussed below. In India, the first O-cell tests were conducted in 2001 for the Rajiv Gandhi (Bandra-Worli) Sea Link project. To date, a total of fifteen O-cell tests have been performed in India. This paper describes the O-cell testing methodology and reviews the results of ten O-cell tests conducted for three different projects in the Mumbai region.

O-cell Testing Methodology

The O-cell is a specialized, sacrificial jack that the Engineer can have installed at the tip of a driven pile or at any depth on the reinforcement cage of a bored pile or auger cast pile. It is calibrated before installation and provides an axial compressive load test as the jack is pressurized from the surface. The

O-cell applies all of the static loading within the pile and requires no external reaction system or dead load at the top of the pile.

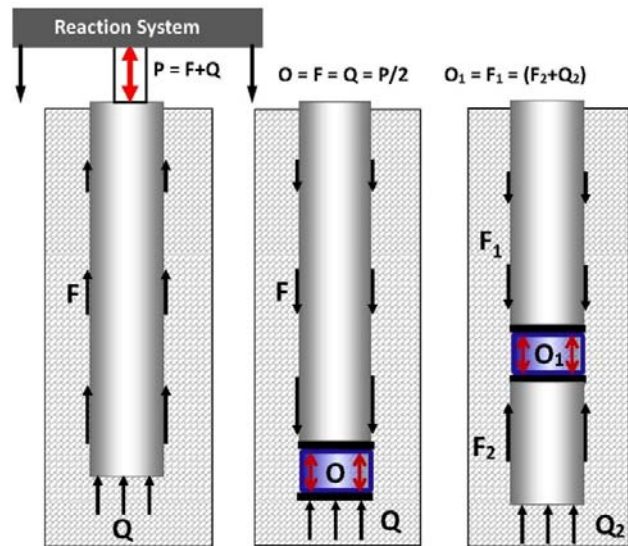


Fig. 1 Top-down test (left) vs. O-cell test (right)

As shown in Fig.1, for a top-down test, the applied compression load P mobilizes the sum of the side shear F and the end bearing Q combine. The engineer can separate these two components approximately by analysis of strain or compression measurements together with modulus and area

estimates. In the Osterberg load test the O-cell also loads the pile in compression, but from the bottom. This provides a major safety advantage for technicians performing the test and for contractors setting up the test. As the O-cell expands, the end bearing Q provides reaction for the side shear F , and vice versa, until reaching the capacity of one of the components or until the O-cell reaches its capacity. In this case, the end bearing and side shear components are measured separately. For a balanced test, where the capacity above and below the O-cell are equal, the O-cell applies only half the load as an overhead jack to mobilize the same total capacity. The O-cell (O_1) may also be moved up the pile to achieve a better balance when needed, so that $F_1 = F_2 + Q_2$.

Load plates welded to the top and bottom of the O-cell spread the axial load over the pile cross-section, and multiple O-cells may be grouped together in an assembly to achieve greater loads. O-cells can also be installed at multiple levels to provide better certainty of fully mobilizing the pile capacity. Tests performed using the O-cell usually follow the Quick Test Procedure found in ASTM D1143, although the Engineer can specify a different loading procedure.

Fig. 2 shows the basic instrumentation for an O-cell test and how small of an area is required to perform the test. For optimum testing efficiency the movements that occur during an O-cell test should be measured by electronic gauges connected to a computerized data acquisition system. The upward movement of the top of the test pile can be measured directly with dial gauges mounted on a reference beam set over the test pile, or now more commonly using digital survey levels. The use of high quality survey levels provides accuracy equal to or better than using reference beams [3]. The total expansion of the O-cell may be measured using telltale rods installed to the top and bottom plates of the O-cell to determine the movement difference. However, the expansion is typically measured directly by at least two linear vibrating-wire displacement transducers (LVWDTs) attached between the O-cell plates. The upward movement of the top of the O-cell may

be measured directly from a pair of telltale rods that extend to the top of the test pile. Alternatively, the pile compression above the O-cell can be measured with telltales and added to the top-of-pile movement to calculate the top-plate movement. Subtracting the upward movement of the top of the O-cell from the total expansion of the O-cell (from the LVWDTs) provides the downward movement of bottom plate.

The reader can deduce from the above that the O-cell load test method provides two separate load-movement curves. One shows the O-cell load vs. the upward movement of the pile section above the O-cell, and the other shows the O-cell load vs. the downward movement below the O-cell. The latter curve includes the end bearing plus any side shear mobilized below the O-cell. The subsequent case histories show examples of these two movement curves.

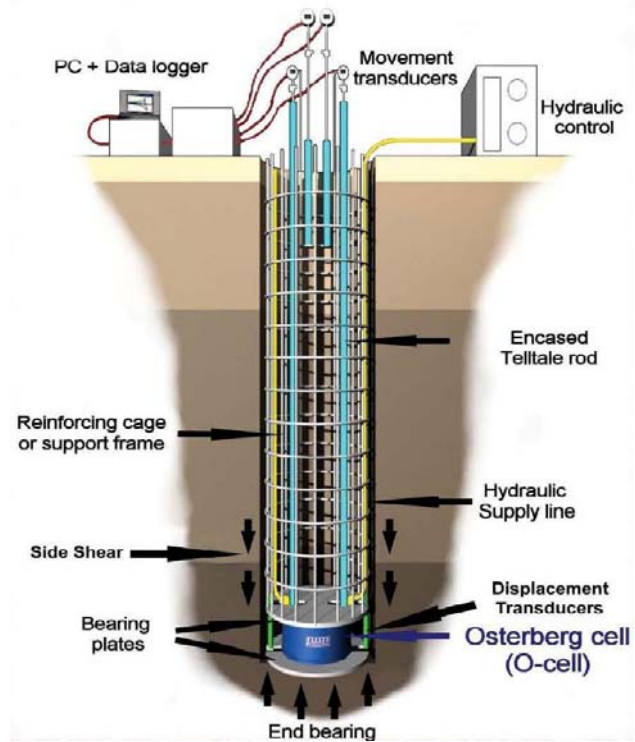


Fig. 2 O-cell test instrumentation (Loadtest USA)

The O-cell method has both advantages and limitations compared to traditional top-load tests. Interpreting the test also requires some consideration of the nature of the loading and movement. Osterberg [1] showed that the direction

of compressive loading has little effect on the mobilized side resistance, so the O-cell test results can be readily combined to develop an equivalent top-load movement curve by simply adding the loads from the two load-movement curves together at similar movements. A refinement to this calculation corrects for the pile compression (typically small), which is greatest near the O-cell during bi-directional loading yet greatest near the pile top for top-loading. A further refinement may use the shear-displacement (T-z) curves obtained from a load-transfer profile based on strain instrumentation, combined with the end bearing curve (Q-z) and pile compression, to calculate the equivalent top-load curve directly. Note that upward O-cell loading must also be corrected by subtracting the buoyant pile weight.

RAJIV GANDHI (BANDRA-WORLI) SEA LINK PROJECT:

The Rajiv Gandhi Sea Link is an eight-lane, 4.7-kilometer long, viaduct bridge with two cable-stayed spans located in Mumbai, India, which connects the provinces of Bandra and Worli. This bridge is a bypass over the sea and will reduce the travel time across Mahim Bay from 40 minutes to just six minutes. Subsurface geology at the project site is highly variable with an uneven foundation bedrock of basalt, volcanic tuff, and breccia overlain by completely weathered rock and river sediments. The thickness of these layers varies throughout the site, and the weathered breccia and tuff are not present at some locations. The bridge foundations included more than 600 large diameter piles; with rock-sockets up to 34 m long. High-capacity, socketed piles were required to support the loads from the bridge structure. The project designers implemented an O-cell test program to verify the design pile capacity and accurately measure the side shear and end bearing resistance. These were the first O-cell tests conducted in India.

Loadtest [4] conducted a total of four O-cell load tests, three multilevel and one single level, as part of the initial phase of construction, prior to finalizing the pile lengths. Because of the variable subsurface geology, these tests were conducted at different locations along the bridge length and the

final pile toe elevations were selected based on the results. The pile dimensions and the number of O-cells in each level are given in Table 1. Hindustan Construction Company constructed the test piles using reverse circulation drilling. Test pile instrumentation included LVWDTs to measure O-cell expansion, telltales to measure pile compression, and strain gauges to estimate the load distribution down the pile.

Table 1 Rajiv Gandhi Sea Link O-cell test piles

Test Pile No.	Diameter (m)	Embedded Length (m)	Number of O-cells	
			Mid-pile	Pile Bottom
2113-1	1.5	19.64	2	2
2113-2	1.5	15.13	2	2
2113-3	1.5	14.65	2	2
2113-4	2.0	14.65	0	2

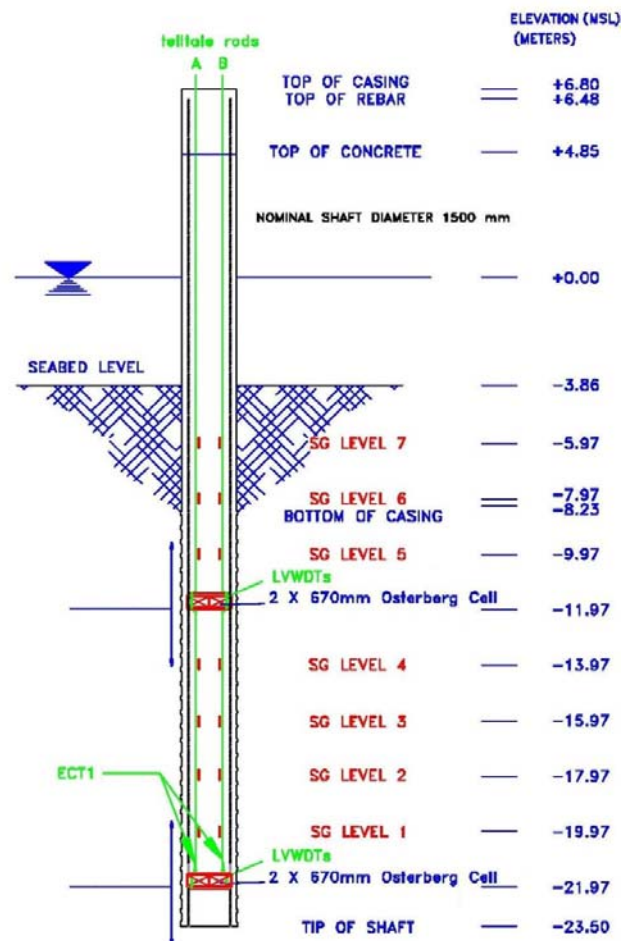


Fig. 3 As-built section, Test Pile 2113-1

As-built sections of Test Piles 2113-1 and 2113-4 are shown in Figs. 3 and 4, respectively. For pile 2113-1, the O-cell assemblies were welded to the rebar cage near the bottom and middle of the pile as shown in Figs. 5 and 6. O-cell tests were conducted as per the client’s loading specifications. Note that the rebar cage cannot extend across an O-cell location and may require special rigging during placement in the pile. The O-cells are welded closed for installation, but these welds break easily during initial loading.

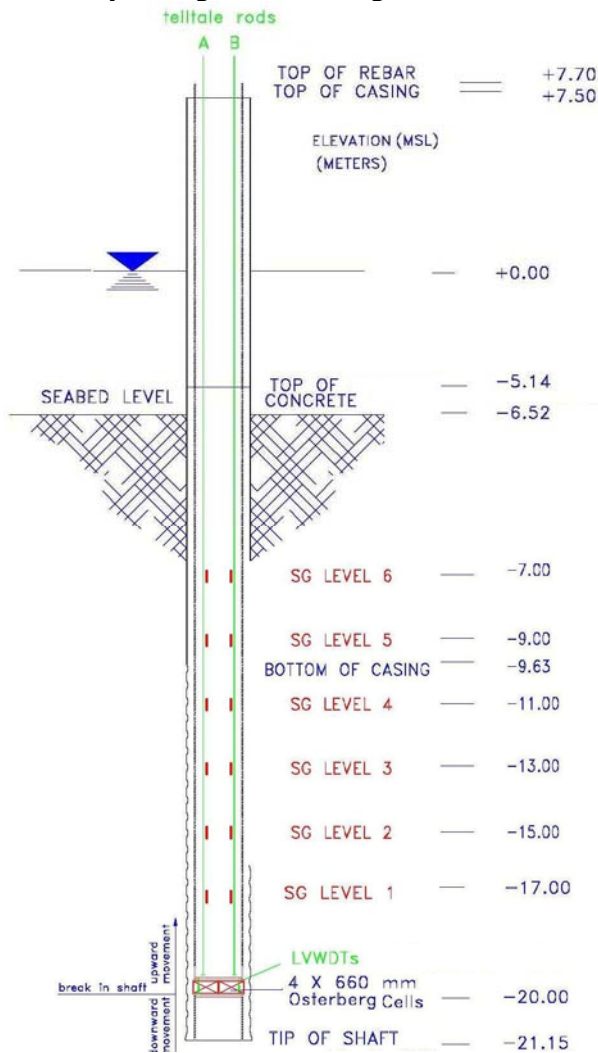


Fig. 4 As-built section, Test Pile 2113-4

For pile 2113-4, a single O-cell level was installed near the pile bottom. Fig. 7 shows the upward and downward load-movement curves for this pile at different loads and Fig. 8 shows the load

distribution estimated from the O-cell loads and the strain gauge readings. Fig. 9 shows the mobilized net side shear for 2113-4, as calculated from the Fig. 8 load distribution curves. Fig. 10 shows the equivalent top-down load curve calculated from the O-cell test results.



Fig. 5 Test Pile 2113-1 lower O-cell assembly



Fig. 6 Test Pile 2113-1 upper O-cell assembly

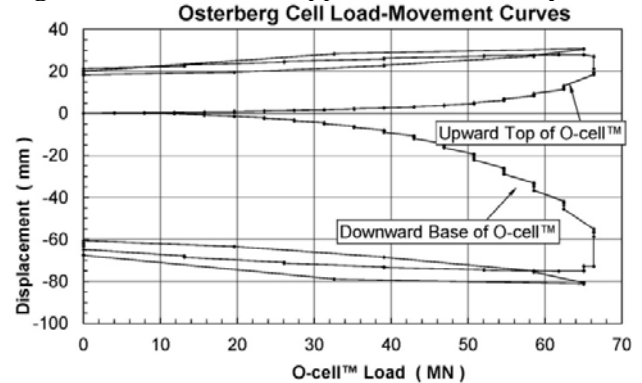


Fig. 7 O-cell load-movement, Test Pile 2113-4

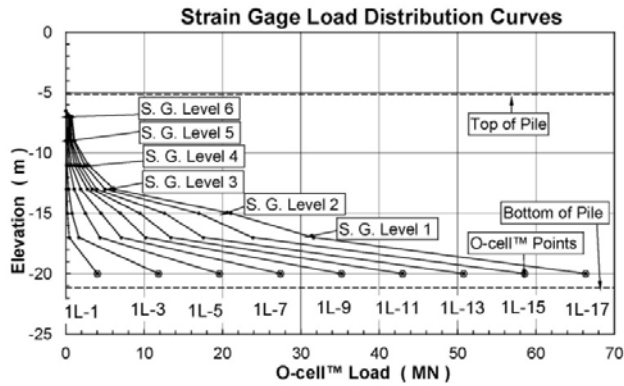


Fig. 8 Load distribution, Test Pile 2113-4

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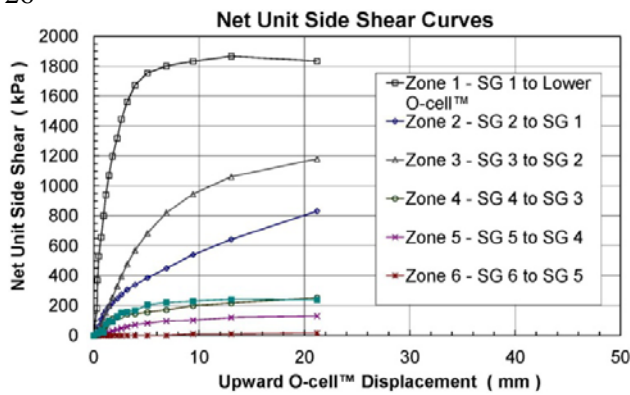


Fig. 9 Mobilized side resistance, Test Pile 2113-4

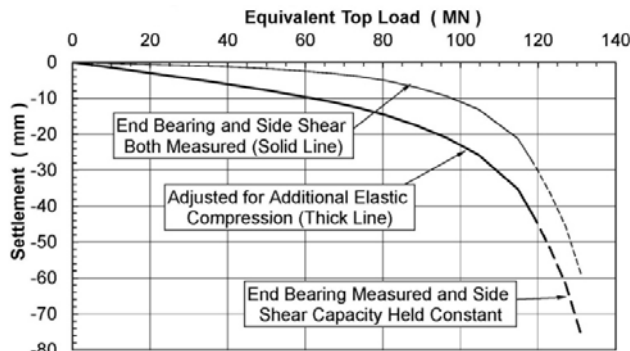


Fig. 10 Top-down load curve, Test Pile 2113-4

Discussion

Table 2 summarizes the O-cell results for all four test piles. O-cell tests were required for these large-diameter, high-capacity load tests performed over water, because the maximum net load (178 MN) far exceeded the capability of top-down testing. The O-cell test was the best and only option for testing full-size piles as it did not require a test frame, large jacks, or reaction piles.

To separate the mobilized end bearing of rock socket accurately from its side shear accurately, three of the test piles were instrumented with two levels of O-cells, one level at the pile tip and another level around one-third length of the pile from its toe. The O-cell test results were used to develop the production pile lengths. At the main pylon, the pile length was shortened by approximately 50%, resulting in a net saving in excess of 500 m (far exceeding the cost of all the O-cell testing).

Table 2 Rajiv Gandhi Sea Link O-cell Results

Test Pile No.	Maximum Load Applied (MN)	Max. Side Shear Mobilized (MPa)	Max. End Bearing Mobilized (MPa)
2113-1	94 (lower) 44 (upper)	2.00	18.5
2113-2	98 (lower) 80 (upper)	2.25	19.6
2113-3	90 (lower) 54 (upper)	3.00	17.5
2113-4	132	1.85	16.9

WORLD CREST TOWERS AT LODHA PLACE, UPPER WORLI, MUMBAI

The iconic World Crest Towers consist of three residential towers with the tallest tower proposed to be 442 m high and 117 stories. Loadtest [5] performed a total of four O-cell tests, two trial pile tests in the pre-design stage and two proof-load working pile tests in the construction stage. After testing, the proof piles were grouted within and around the O-cell to reestablish the pile integrity. Table 3 provides the basic test pile information.

Table 3 World Crest Towers O-cell test piles

Test Pile No.	Designation	Diameter (m)	Length (m)
2873-1	Test pile	1.20	26.7
2873-2	Test pile	1.20	25.9
2894-1	Working Pile	1.20	19
2894-2	Working Pile	1.20	19

Subsurface geology at the project location consists of a 3-meter thick fill layer overlaying weathered and slightly weathered Tuff layers. Valecha

Engineering Ltd. performed the excavation and construction of the rock-socketed, bored piles. Paired compression telltales and pile toe telltales were used to measure the pile compression above and below O-cell assembly, respectively. Seven levels of paired strain gauges, three below and four above the O-cell, were installed to estimate the applied load distribution. For all the four piles, the O-cell assembly was located 4 m above the pile tip. Fig. 11 shows an as-built section of Test Pile 2873-1. Fig. 12 shows the O-cell assembly welded to the rebar cage for Test Pile 2873-1.

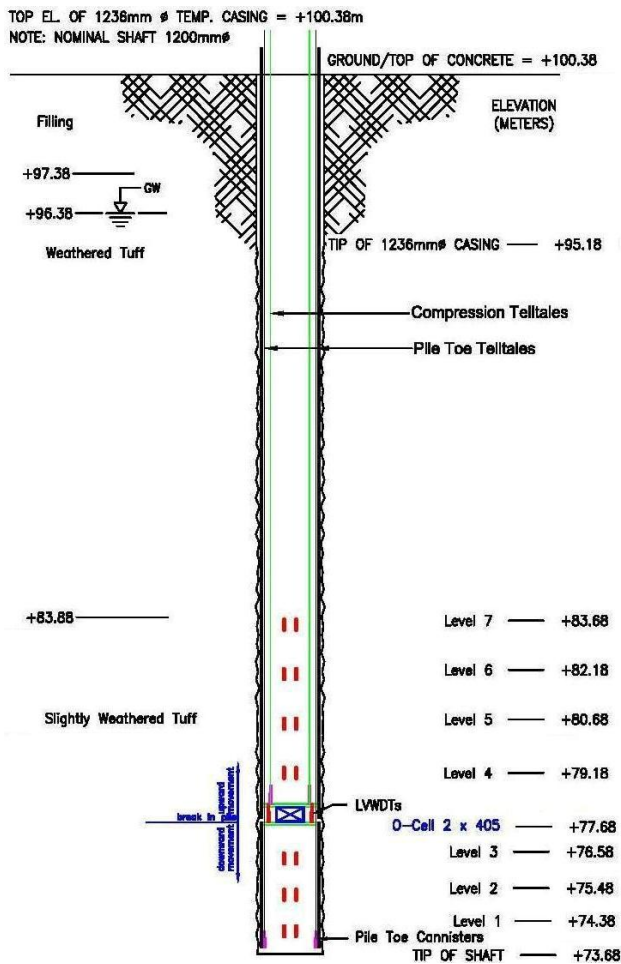


Fig. 11 As-built section, Test Pile 2873-1

The maximum bi-directional load applied for these tests was about 38 MN (19 MN in each direction). Fig. 13 shows the upward and downward movement of the O-cell with respect to load. Fig. 14 shows the strain gauge and O-cell load

distribution at different load increments. Note that Fig. 14 shows that no load was transferred to the pile toe in end bearing, indicating that the rock socket supported all of the downward O-cell load. Table 4 summarizes the results of the four O-cell tests. Fig. 15 uses the load-deflection curves from Fig. 13 to calculate an equivalent top-down curve for Test Pile 2873-1.



Fig. 12 O-cell assembly welded to Test Pile 2873-1

Discussion

The geotechnical investigation reported the saturated crushing strength as 1.6 to 3.1 MPa for the highly weathered tuff rock and 1.5 to 9.6 MPa for the moderately weathered tuff rock, estimating the design side resistance of the pile as 0.1 MPa. Based on the O-cell strain gauge data in Fig. 14,

the maximum side resistance actually measured in the tuff rock was calculated as 1 to 2 MPa, more than ten times the design estimate. This positive disparity between design and measured pile resistance is often observed for O-cell tests performed around the world, especially for piles socketed into rock [2]. Using the O-cell test results, the final pile design lengths were shortened from 26.5 m to 19 m. Tests of the shortened production piles measured nearly as much capacity as the test piles. For all four O-cell tests, the rock socket supported the applied load completely in side shear resistance without transmitting any load to the pile toe. If the end bearing had been included in the final design capacity, then the production lengths could have been reduced further. This illustrates the potential economic savings from O-cell testing, provided they are performed prior to finalizing the design.

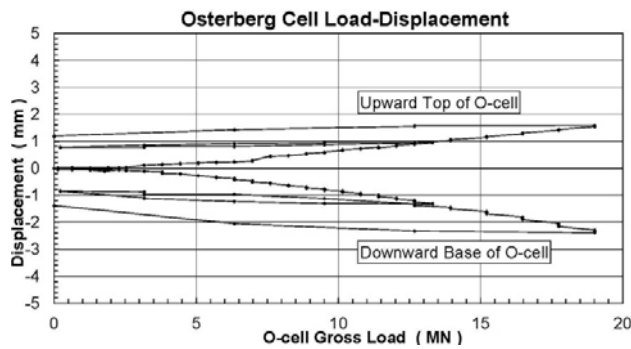


Fig. 13 O-cell load-movement, Test Pile 2873-1

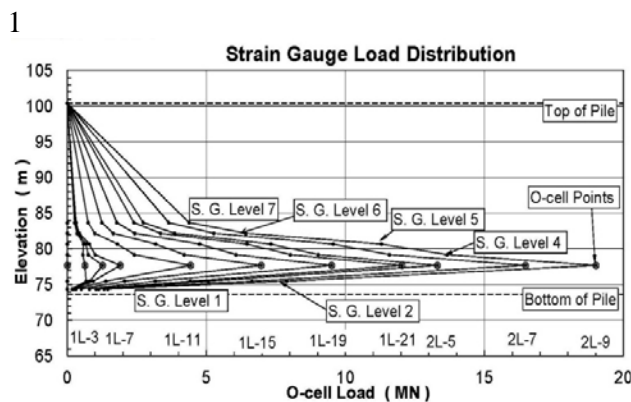


Fig. 14 Load distribution, Test Pile 2873-1

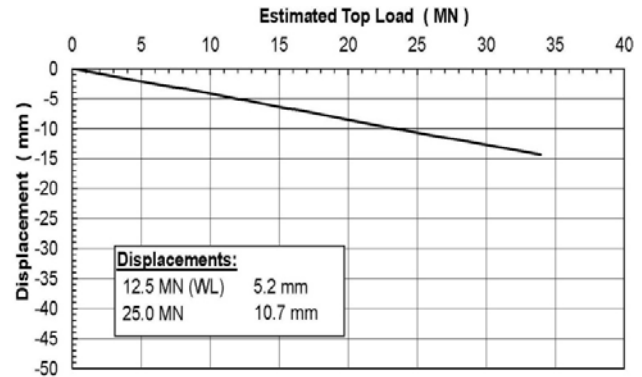


Fig. 15 Top-down load curve, Test Pile 2873-1

Table 4 World Crest Towers O-cell Results

Test Pile No.	Maximum Load Applied (MN)	O-cell expansion (mm)	Max. Side Shear Mobilized (MPa)	Max. End Bearing Mobilized (MPa)
2873-1	38	3.97	1.55	None
2873-2	38	14.10	2.00	transferred
2894-1	34	3.58	1.66	to toe
2894-2	31	3.21	1.00	

INFRA WADALA, MUMBAI

Two single level O-cell static loading tests were conducted in the pre-design phase of the “Infra Wadala” high-rise condominium construction project. Two 1000 mm diameter bored trail piles, TP-1 and TP-2, socketed in rock were constructed to embedment depths of 29.92 m and 19.40 m, respectively. For both test piles, the O-cell assembly was located 1 m above the pile toe. Lodha Crown Buildmart Pte. Ltd. completed the excavation and construction of both rock-socketed test piles.

Subsurface geology at the test pile location primarily consists of 12- 15 m depth marine clay underlain by weathered to hard tuff rock. TP-1 was instrumented with five levels of vibrating wire strain gauges and TP-2 was instrumented with four levels, with four strain gauges per level. Note that four gauges per level are preferred to check the average stress from the two opposing pairs of gauges. Paired compression telltales were used to measure the compression in upper shaft above the O-cell.

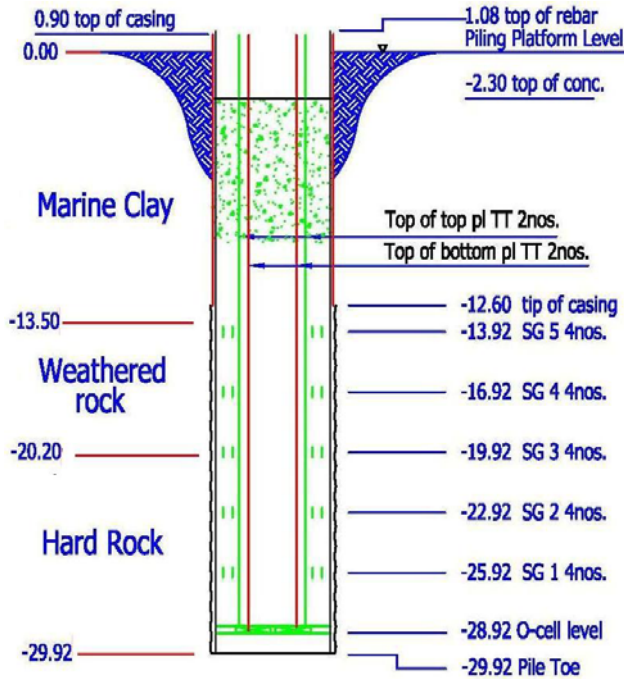


Fig. 16 As-built section, Infra Wadala TP-1

Fig. 16 shows an as-built section of TP-1. Table 5 summarizes the results of the O-cell tests reported by Loadtest [6]. The mobilized unit end bearing at different O-cell displacements is shown in Fig. 17. The high capacity of these two test piles is similar to the previous examples and further demonstrates the value of measuring pile performance for better design.

Table 5 Infra Wadala O-cell Results

Test Pile No.	Maximum Load Applied (MN)	Zone displacement (mm)	Max. Mobilized Side Shear (MPa)	Max. End Bearing Mobilized (MPa)
TP-1	20	2.70	0.38	10.59
TP-2	20	3.18	1.54	7.53

Note: Zone displacement represents the displacement at which the corresponding side shear was mobilized

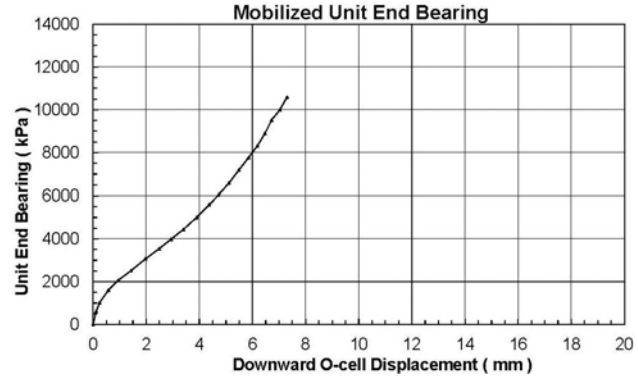


Fig. 17 Mobilized unit end bearing for TP-1

CONCLUSIONS

1. The test results from India presented herein demonstrate the ability of the O-cell to safely mobilize and measure high axial compressive capacities for full-scale, large-diameter piles.
2. The O-cell test method often mobilizes most of the available side shear and end bearing resistance in soil profiles. Rock socket strengths are often underestimated. Hence, the O-cell is a very good tool to optimize the pile design with potentially significant economic savings.
3. Compared to the traditional top-down testing method, the O-cell test is a very safe and economical test, especially for high test loads. The O-cell test does not require any loading frame or reaction piles, and it can be conducted under restrictive site conditions, such as over water, within foundation pits, underneath structures, and in limited space. It often makes an otherwise impractical test situation practical.
4. The typical O-cell location is either at or near the pile tip, and therefore the end bearing can be easily separated from the side resistance. With the use of strain gauges, the soil-pile resistance at different depths along pile length can be accurately characterized.
5. By using multiple levels of O-cells, it possible to completely mobilize and accurately measure both the end bearing and side shear of longer rock sockets.
6. Loadtest reports that their worldwide O-cell test experience indicates that design assumptions typically under predict the actual pile capacity, and that for rock sockets the factor may be 10 or more.

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