양방향재하시험의 국외 적용 사례
A Case Study on Application of O-cell Test in Oversea

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SYNOPSIS : 대구경 현장타설말뚝에 대한 시험하중의 증가와 함께 적용이 활성화되고 있는 오스터버그 셀(Osterberg cell)방식이 적용된 국외의 4 개소 시험결과에 대하여 소개하였다. 사례연구의 대상이 된 4 개소 시험말뚝은 일반적인 시험보다는 결과상의 특징이 있어 현재 및 향후 동일한 시험방법이 적용될 경우 고려될 수 있는 내용을 중심으로 기술하였다. 이들 말뚝시험에서는 가장 전형적으로 지지력의 균형이 이루어져 말뚝의 극한현상이 발생되지 않아 설계하중을 충분히 확인한 경우뿐 아니라 선단지지력이 부족하여 선단 그라우팅 후 재시험을 한 경우, O-cell을 말뚝의 선단에 가장 근접하여 설치 한 후 시험한 경우, 그리고 다단면(multi-level test)시험이 수행되었던 예 등을 살펴보았다.

Keywords : Osterberg cell testing, drilled shafts, bored piles, case histories, load testing, unit resistances, load-movement curve

1. Introduction

The development and use of the Osterberg cell, or O-cell, method for the high capacity, static testing of bored piles gives engineers a new and powerful tool to evaluate the effects of pile construction techniques. Simply put, the O-cell is a sacrificial jack-like device which the Engineer can have installed at the tip of a driven pile or at any elevation on the reinforcement cage of a bored pile. The O-cell method has been using about for 20 years, and the technique was described and introduced by many researchers (Osterberg, 1989; Schmertmann, 1998; England, 2002; Molnit, 2006).

Herein we review the Osterberg Cell, or O-cell, method for performing large capacity load test on bored piles(drilled shafts) in a few oversea countries. Among a lot of numbers of O-cell test, four selected case histories are introduced to enhance a possibility of application of O-cell method. Through an analysis of cases such as re-testing after toe grout, the closest case of O-cell installation to the pile tip and the multi-level test as well as ideal balance of resistance components, it is concluded that the O-cell method could be useful and effective to verify the construction quality assurance and to give a good tool for design feedback work.

2. Case histories

Table 1 shows a brief characteristics of the test piles which is analyzed here.

Table 1. A brief information of test piles

Project Name	Test Pile Information			Ground Condition of Pile tip	Test Load (MN)
	Pile designation	Diameter (mm)	Penetration Depth(m)		
Condominiums-Singapore	TP-CS	1200	24.4	siltstone	16.6
Crescent Bridges- Dubai	TP-CD	1500	11.7	calcarenite rock	15.5
Road-Republic of Palau	TP-RP	1500	22.5	volcanic breccia	29.5
Sea Link Location-India	TP-SI	1500	19.6	breccia/lapilli tuff	47.1

2.1 Condominiums-Singapore

The 1200 mm test pile was constructed wet using bentonite. The O-cell^{TM} assembly (four 400-mm O-cells^{TM}) was located 2.35 m above the tip of pile. The contractor removed the temporary 1230-mm O.D. casing immediately after concrete placement. No unusual problems occurred during construction of the pile. The sub-surface stratigraphy at the test pile location is reported to consist of clayey silt up to a depth of 2 m underlain by 4 m thick of clayey sand. Between depths 6 m and 10 m, the soil is identified as silty sand with very weak siltstone fragments. From depth of 12 m to 17.5 m, silty sand with siltstone fragment was encountered. Very dense silty sand with siltstone fragment was identified between depths of 17.5 m and 20 m. The material below depth of 20 m to the pile

Combined End Bearing and Lower Side Shear: The maximum downward applied load, maintained for 15 -minutes, was 16.6 MN(Figure 1). At this loading, the average downward movement of the O-cell^{TM} base was 32.9 mm. The side shear capacity of the 2.35 m pile section below the O-cell^{TMTM} is calculated to be 7.5 MN assuming a unit side shear value of 852 kPa and a nominal pile diameter of 1200 mm. The maximum applied load to end bearing is then 9.1 MN and the unit end bearing at the base of the pile is calculated to be 8037 kPa at the above noted displacement.

Upper Side Shear: The maximum upward applied net load, maintained for 15- minutes, was 16.0 MN(Figure 1). At this loading, the upward movement of the O-cell top was 15.3 mm. Assuming a nominal pile diameter of 1230 mm (EL. +104.27 to +95.84 m) and 1200 mm (EL. +95.84 to +82.84 m), the average unit side shear capacity of the 21.43 m pile section above the O-cells is calculated to be 196 kPa.

Strain Gage Results: On the day of the test, the concrete unconfined compressive strength was reported to be 44.0 MPa. The ACI formula (Ec=57000SQRT(f'c)) was used to calculate an elastic modulus for the concrete. This, combined with the area of reinforcing steel and nominal pile diameter, provided an average pile stiffness (AE) of 44200 MN in the upper cased portion of the pile, 33300 MN above the O-cell and 32700 MN below the O-cell. Shear values follow in Table 2.

The Osterberg cell load test was conducted as follows: The four 400-mm diameter O-cells, with their base located 0.70 m above the tip of pile, were pressurized to assess the combined end bearing and lower side shear characteristics of the pile section below the O-cells and the upper side shea. During the first loading cycle, the O-cells were pressurized in 18 equal loading increments to 24.82

Table 2. Average Net Unit Side Shear Values for 1L-34 for Pile TP-CS

Elevation (m)	Load Transfer Zone	Net Unit Side Shear*
104.27-99.74	Zero Shear to SG 8	7 kPa
99.74-97.74	SG 8 to SG 7	40 kPa
97.74-94.74	SG 7 to SG 6	90 kPa
94.74-91.74	SG 6 to SG 5	103 kPa
91.74-89.24	SG 5 to SG 4	532 kPa
89.24-84.34	SG 4 to SG 3	239 kPa
84.34-82.84	SG 3 to O-cell level	415 kPa
82.84-81.74	O-cell to SG 1	852 kPa

* For upward-loaded shear, the buoyant weight of pile in each zone has been subtracted from the load shed in the respective zone.
Note: SG(Strain Gage) 2 data yielded higher loads than applied by O-cell and are not included in the analysis.

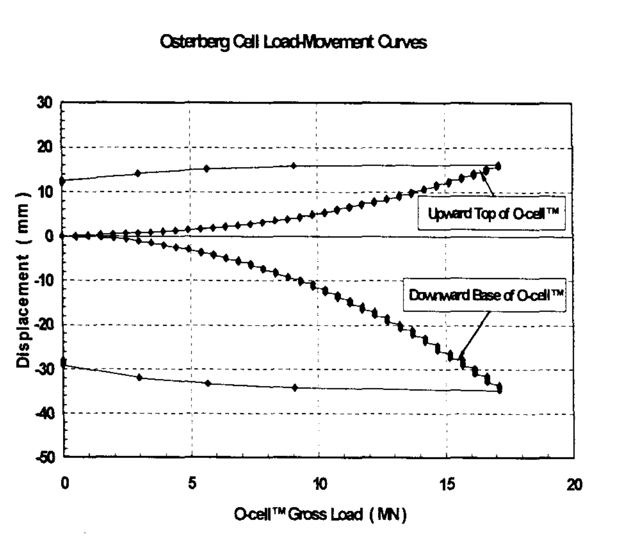


Figure 1. Load-Movement Curve for TP-CS

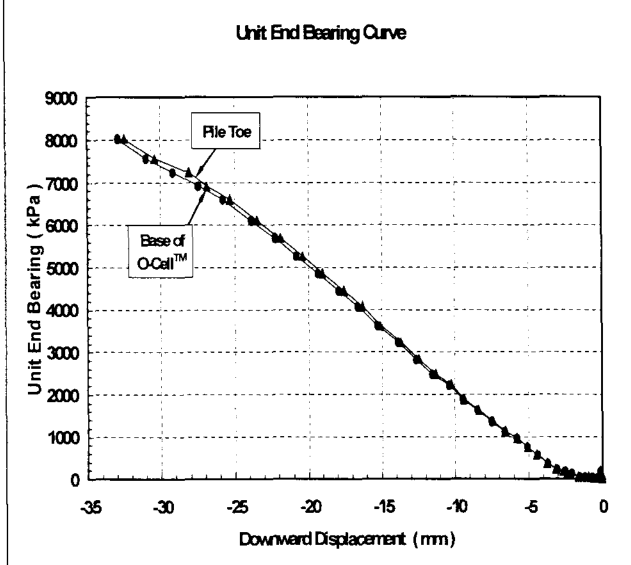


Figure 2. Unit End Bearing Curve for TP-CS

MPa (3600 psi) resulting in a bi-directional gross O-cell load of 8.83 MN. Load Cycle 1 was halted by the client to provide access to base grouting after the first loading cycle, and the O-cells were then depressurized in six decrements. The test pile was base-grouted. Note that during the grouting operation the O-cells were pressurized to 6.89 MPa (1000 psi) in order to insure that no grout intruded into the hydraulic system. After a 7-day grout curing period, Cycle 2 was initiated in order to measure the effect of base grouting on pile end bearing performance.

The O-cells were re-pressurized in 26 equal loading increments to 35.85 MPa (5200 psi) resulting in a gross load of 12.73 MN. An unexpected pressure loss in the system was encountered and the pile was unloaded in one decrement. After repairing the hydraulic system, testing resumed. During Load Cycle 3 the

O-cells were repressurized in 14 loading increments to 41.37 MPa (6000 psi), resulting in a gross O-cell load of 14.68 MN upward and downward. The O-cells were then unloaded in ten decrements and the test was concluded. Figure 3～Figure 6 shows the analyzed test results.

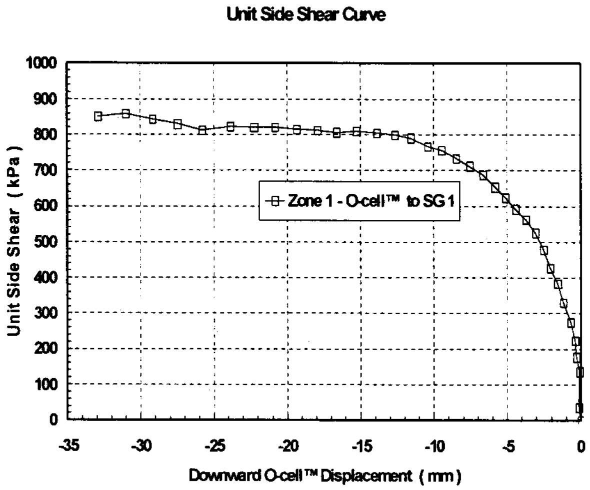


Figure 3. Unit Side Shear Curve for TP-CS

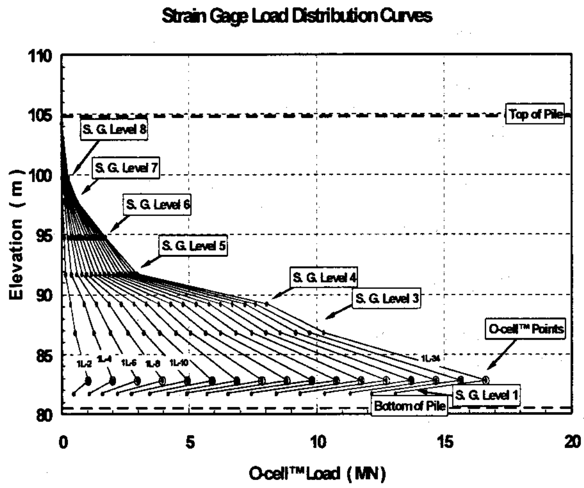


Figure 4. Strain Gage Load Distribution Curves for TP-CS

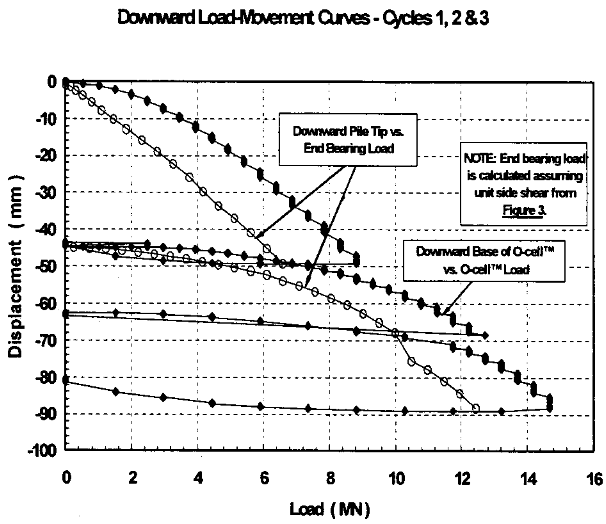


Figure 5. Downward Load-Movement Curves for TP-CS(Cycles1, 2, 3)

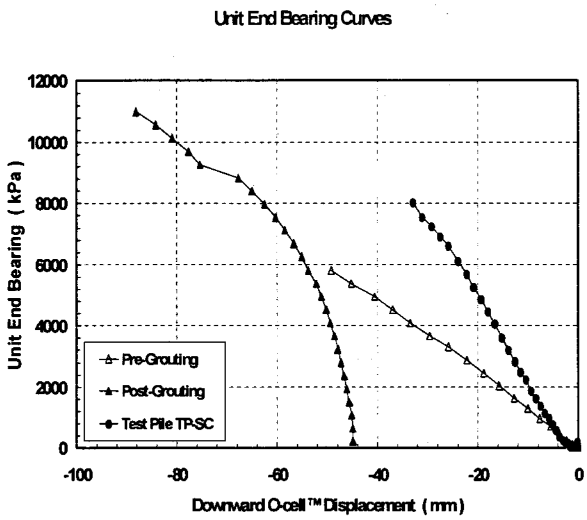


Figure 6. Unit End Bearing Curves for TP-CS

2.2 Crescent Bridges- Dubai

Construction of the pile, TP-CD, began by vibrating the permanent 1524-mm O.D. casing to -13.40 mDMD. The pile was excavated wet to a final pile tip elevation of - 20.60 mDMD using a rock digging bucket. After completing the excavation the shaft was cleaned by the airlift method via a 100-mm pipe. The rebar cage with attached O-cell® assembly was lowered into the shaft and suspended from hangers. The O-cell®

assembly (one 540-mm O-cell®) was located 1.75 m above the tip of pile. Concrete was placed into the shaft up to 0.9 m below seabed level using a tremie pipe. No unusual problems occurred during construction of the pile. The sub-surface stratigraphy at the test pile location is reported to consist of a calcarenite rock layer from seabed to elevation -11.6 mDMD. From elevation -11.6 mDMD to -14.6 mDMD the soil consists of a sandstone rock layer, underlain by another calcarenite rock layer.

The Osterberg cell load test was conducted in three cycles, as follows: The 540-mm diameter O-cell®, with its base located 1.75 m above the tip of pile, was pressurized to assess the combined end bearing and lower side shear characteristics of the pile section below the O-cell® and the upper side shear above.

In Cycle 1, the O-cell® was pressurized in one loading increment to 24.13 MPa (3500 psi) resulting in a bi-directional gross O-cell® load of 4.06 MN. The O-cell® was then depressurized in four decrements.

In Cycle 2, the O-cell® was pressurized in three loading increments to 35.85 MPa (5200 psi) resulting in a bi-directional gross O-cell® load of 5.99 MN. The O-cell® was then unloaded in six decrements. depressurized in six decrements and the test was concluded.

The compression of the 1.75 m pile section below the O-cell®, calculated by subtracting the pile tip telltale movement from the bottom plate telltale B movement (which was located closest to the tip telltale), is 0.46 mm. Assuming this compression is entirely due to a uniform shear distribution along the lower pile section resulting in a bi-directional gross O-cell® load of 15.45 MN. The O-cell® was then of 6.90 MN at the top of the section and 0.00 MN at the bottom), a stiffness of 13200 MN is computed using the formula d = 0.5 PL / AE. Note that this stiffness is

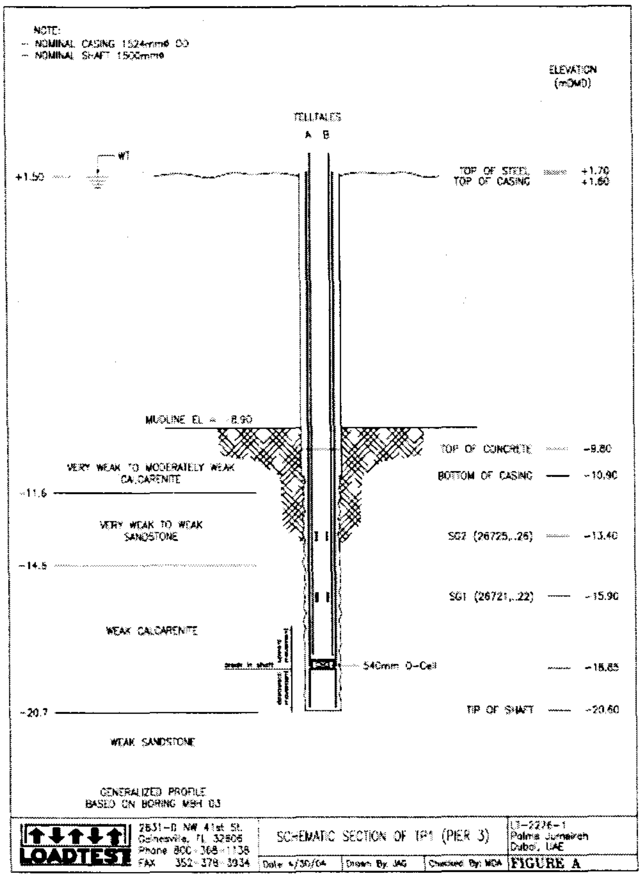


Figure 7. Schmatic Section of Test Pile(TP-CD)

low compared to the stiffness computed using the ACI method (see below), but it is only applied to the lower pile compression (which may include elements such as concrete crushing in addition to elastic compression).

The maximum downward applied load was 15.45 MN. At this loading, the average downward movement of the O-cell ® base was 44.5 mm. During the Cycle 3 of the test the downward movement increased abruptly load of 7.8 MN. At this point of the test the downward load resistance shifted from side friction only to a combination of side friction and end bearing. Assuming no end bearing is mobilized, the maximum unit skin friction would be 837 kPa for a movement of 1.2 mm. The following analysis is an attempt to separate the pile section below the O-cell® into shear and end bearing components using the telltale data since no strain gages were placed in this section of the pile. Load distribution curves from strain gages is shown in Figure 8.

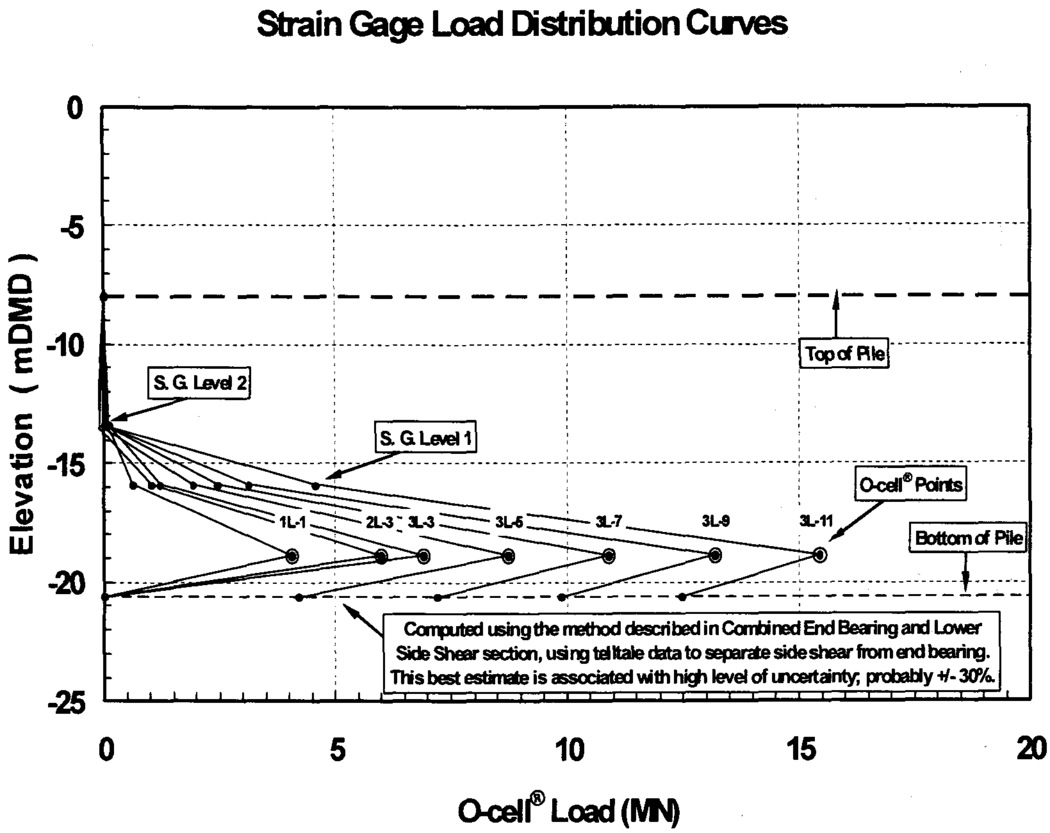


Figure 8. Strain Gage Load Distribution Curves for TP-CD

2.3 Road Project-Republic of Palau

The 1500 mm test pile was constructed wet using water with a tip elevation of -24.61 m. The pile was excavated using a grab, and the rock socket a chisel and grab. Prior to placing the rebar cage and concrete, the pile was cleaned using an airlift. The O-cell assembly (one 870-mm O-cell) was located 0.15 m above the tip of pile. The contractor removed the inner 1500-mm O.D. casing immediately after concrete placement. Some problems were encountered during the grouting of the space below the O-cell assembly. The geological profile at the test pile location is reported to consist of layers silty clay and sand to a depth of 11 m underlain by 1.5 m of clayey silt and subsequently volcanic breccia to an undetermined depth.

The construction of the pile included placing two lines of PVC pipe, starting at the top of pile and terminating at the top of the bottom plate to vent the void created in the pile at the base of the O-cell. In addition, they permitted the application of water in the fracture plane to maintain equilibrium with the existing water table. The shape of the downward load-movement curve(Figure 10) as well as the differential opening of the O-cell indicates non-uniform conditions of the grouted space below the O-cell assembly. The curve has been extrapolated backwards from 1L-13 in order to assess the probable load-movement characteristics of a pile without an O-cell and grouting in the base area. This linear regression indicates an ""origin"" for the downward load-movement curve at -21.1 mm, thus suggesting a maximum downward movement at 1L-27 of -15.0 mm.

It is important to remember that the problems encountered in construction the grout layer below the O-cell level would not occur in a normal production pile. It is therefore likely that the pile base would behave more like the suggested linear regression or even better.

Figure 11 shows the unit side shear vs. elevation curve analyzed from strain measurement. The O-cell installed into the rebar cage is shown in Figure 12(a) and the testing set-up can be seen in Figure 12(b).

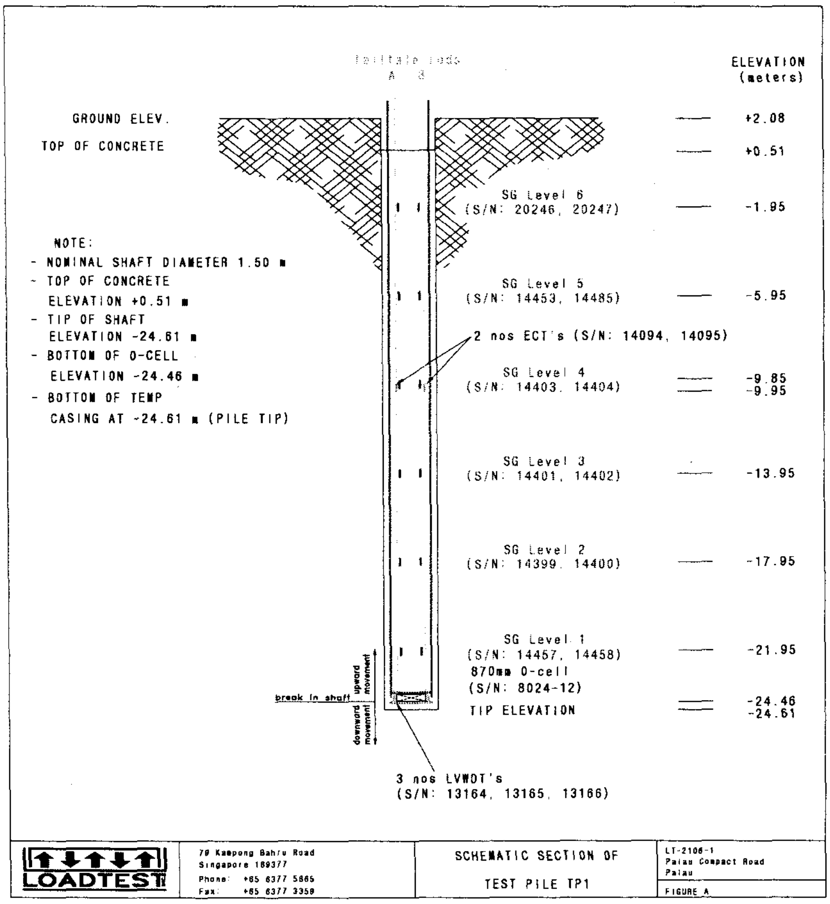


Figure 9. Schmatic Section of Test Pile(TP-RP)

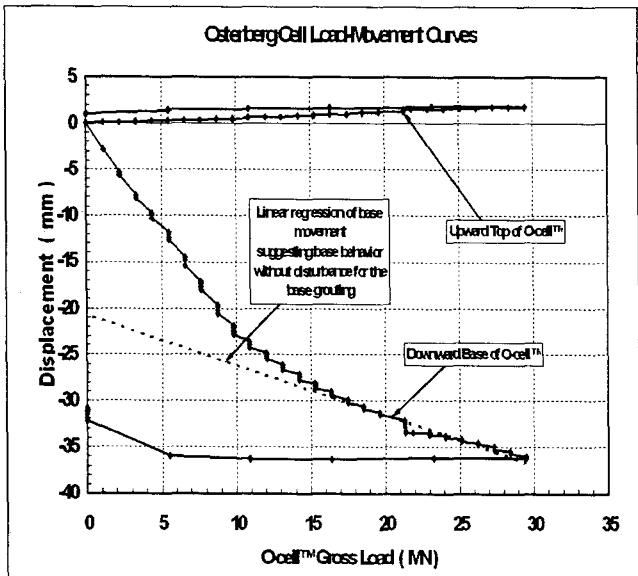


Figure 10. Load-Movement Curves for TP-RP

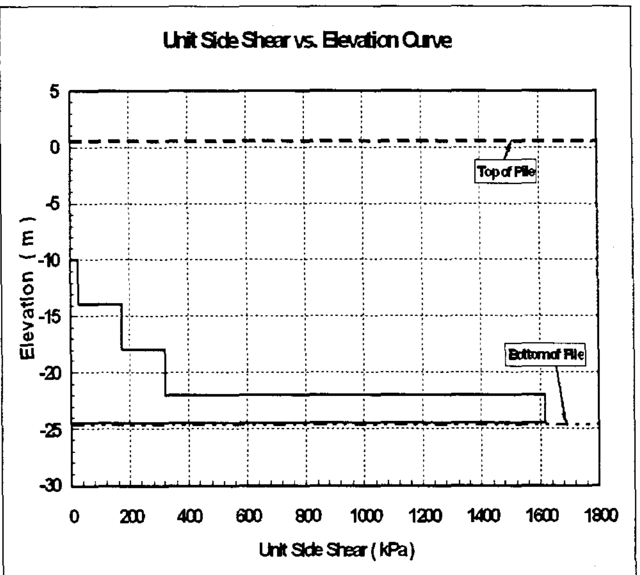
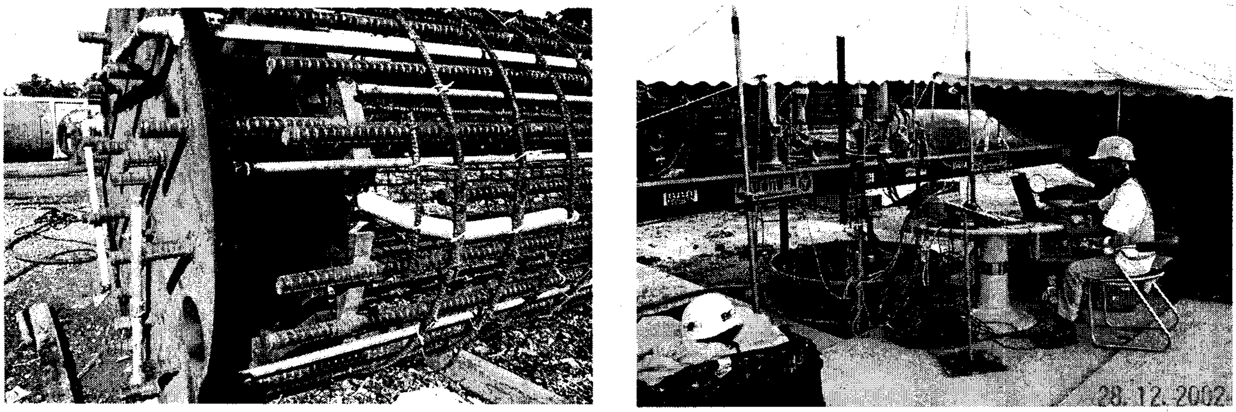


Figure 11. Unit Side Shear Curves for TP-CD



(a) (b)

Figure 12. Installed O-cell and Testing Set-up; (a)O-cell (b)Testing Set-up

2.4 Sea Link Location-India

The 1500 mm test pile was constructed wet using water with a tip elevation of -23.50m(Figure 13). The pile was drilled using a reverse circulation drill rig. After airlifting the tip of the pile, the rebar cage, with attached O-cells and instruments, was lowered into the shaft until the O-cells were at their target elevation. Concrete was placed into the pile using a 250-mm tremie pipe. During concreting problems occurred when concrete blocked the tremie (possibly due to large, angular aggregate). The tremie had to be fully extracted and reinserted during concreting below and around the upper O-cell assembly. The lower and upper O-cell assemblies (two 670-mm O-cells each) were located 1.53 m and 11.53 m above the tip of pile, respectively. The sub-surface stratigraphy at the test pile location is reported to consist of river sediment to elevation -7.85 m underlain by breccia and lapilli tuff (bedrock) to an undetermined depth.

The test was carried out in five stages as follows:

Stage1: In the first stage the two 670-mm diameter lower O-cells, with their base located 1.53 m above the tip of pile, were pressurized as an initial proof test to assess the combined end bearing and lower side shear characteristics of the lower pile section.

Stage 2: After unloading the lower O-cells, the two 670-mm upper O-cells, located 10.00 m above the base of the lower O-cells, were pressurized to assess the shear characteristics of the pile section above the upper O-cells by using the middle side shear as reaction. The lower O-cells were left free to drain (no load transfer through the O-cells to end bearing). The upper O-cells were pressurized.

Stage 3: Testing of the upper pile section resumed. The upper O-cells were pressurized in 14 loading increments to 46.20 MPa (6700 psi) resulting in a maximum bi-directional gross O-cell load of 21.9 MN. The loading continued ; however, the upper O-cells began expanding rapidly and pressure could not be maintained.

Stage 4: In the fourth stage, the lower O-cells were repressurized in 29 loading increments to 99.8 MPa (14500 psi)resulting in a bi-directional gross O-cell load of 47.1MN in order to determine the ultimate side shear capacity of the middle pile section and the capacity of the combined lower side shear and end bearing of the lower pile section. The upper O-cells were left free to drain in order to isolate the middle pile section.

Stage 5: The lower O-cells were then repressurized in five loading increments to a bi-directional gross O-cell load of 47.1 MN upward and downward at 5L-5 in order to demonstrate that no weakening of the pile occurred as a result of the load test.

Combined End Bearing and Lower Side Shear: The maximum downward applied load during Stage 4 was 47.1 MN(Figure 14(b)). At this loading, the average downward movement of the lower O-cell base was 1.8 mm. The side shear capacity of the 1.53 m pile section below the O-cell is calculated to be 14.4 MN assuming a unit side shear value of 1994 kPa and a nominal pile diameter of 1500 mm. The maximum applied load to end bearing is then 32.7 MN and the unit end bearing at the base of the pile is calculated to be 18531 kPa at the above noted displacement.

Middle Side Shear: The maximum upward applied net load during Stage 4 was 46.2 MN (Figure 14(b)). At this loading, the upward movement of the lower O-cell base was 2.8 mm. The high strains logged by the level 4 strain gauges (immediately below the upper O-cells) support this assumption.

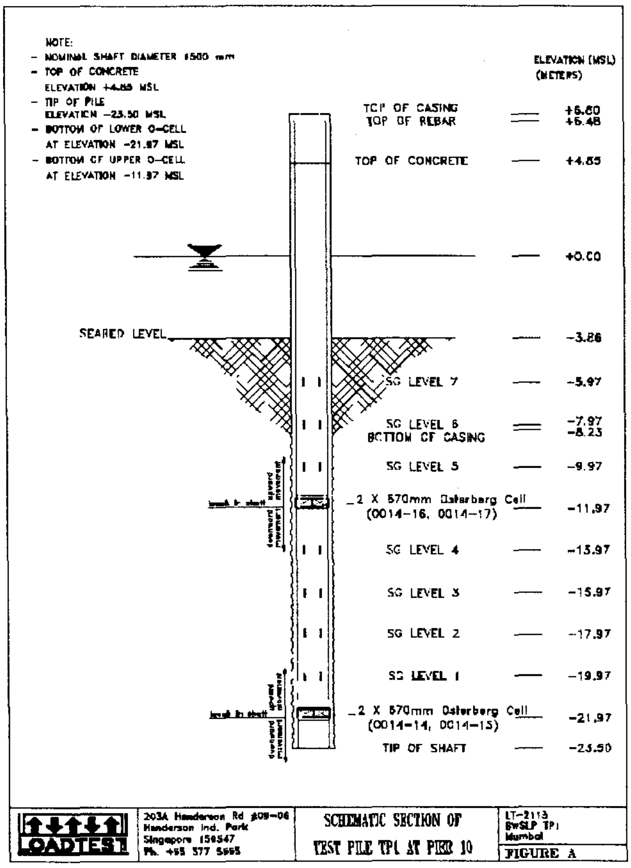


Figure 13. Schematic Section of TP-SI

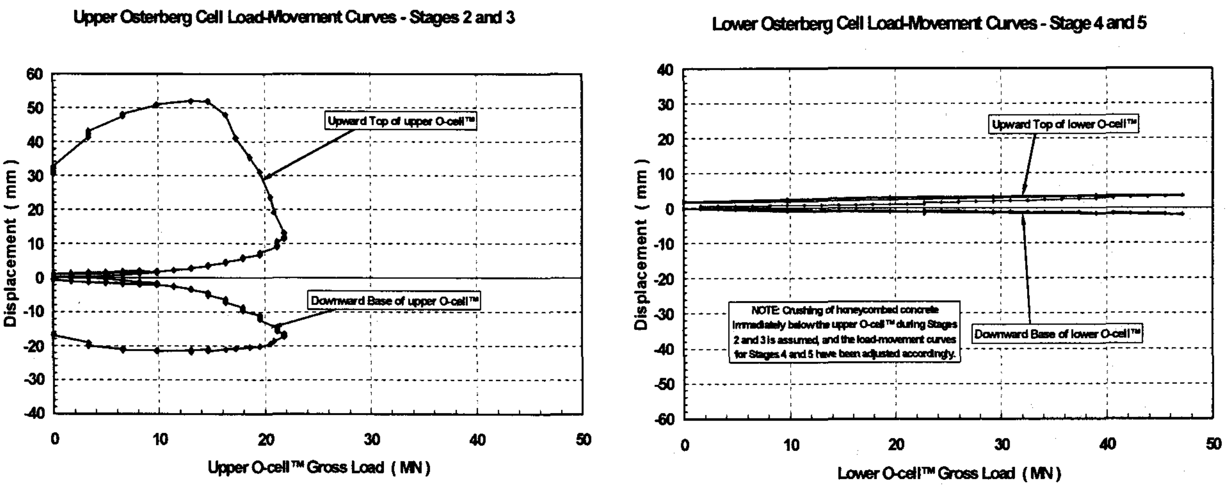
The following Table 3 below summarizes the five stages of loading:

Table 3. Summary of the Five Loading Stages

Stage	Load Interval	Upper O-cell			Lower O-cell		
		Max Q_{gross}	O-cell Hydraulics System	Total Expansion (mm)	Max Q_{gross}	O-cell Hydraulics System	Total Expansion (mm)
1	1L-1 to 1L-20	0.0	Closed	+0.0	19.5	Pressurized	+1.9
2	2L-1 to 2L-6	9.8	Pressurized	+3.3	0.0	Draining	+0.7
3	3L-1 to 3L-20	21.8	Pressurized	+69.0	0.0	Draining	+0.6
4	4L-1 to 4L-29	0.0	Draining	+45.8	47.1	Pressurized	+5.5
5	5L-1 to 5L-5	0.0	Draining	+45.8	47.1	Pressurized	+5.7

Upper Side Shear: The maximum upward applied net load during Stage 3 was 21.2 MN which occurred at load interval 3L-14 (Figure 14(a)). At this loading, the upward movement of the upper O-cell top was 13.0 mm. The following section provides net unit side shear estimates based on strain gauge data.

Strain Gauge Results: An average pile stiffness (AE) of 61700 MN between the two levels of O-cells was computed using the concrete cube strength test results. However, since the pile was



(a) Stages 2 and 3 (b) Stages 4 and 5

Figure 14. Load–Movement Curves for TP–SI

3. Summary

The O-cell test method almost always permits the testing of full scale bored piles or even barrettes, with either side shear or end bearing reaching an ultimate load value. Testing full scale, and reaching an ultimate help greatly for detecting poor construction and in deciding if and how to improve the technique. When the engineer limits the loading to twice the design load, the applicability of the O-cell method can be very useful and helpful.

Through an analysis of cases such as re-testing after toe grout, the closest case of O-cell installation to the pile tip and the multi-level test as well as ideal balance of resistance components, it is concluded that the O-cell method could be useful and effective to verify the construction quality assurance and to give a good tool for design feedback work.

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