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Back analysis of O-cell pile load test using FEM

Analyse régressive de test de charge de pieux de cellule O, utilisant la méthode FEM

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ABSTRACT
A back analysis was carried out to evaluate the performance of Osterberg cell pile load test. The finite element code PLAXIS was used for the numerical simulation of the load-settlement responses and the load transfer characteristics of conventional static and Osterberg cell pile load tests. The comparison between the calculations and measured field data suggests that the Osterberg cell test can be a good substitute for the conventional pile load test. The differences in the load transfer characteristics between conventional static pile load test and Osterberg cell test result in a slightly higher ultimate capacity for the Osterberg cell test.

RÉSUMÉ
Une analyse a été effectuée pour évaluer la performance de l'essai de charge statique d'Osterberg. Le code des éléments finis PLAXIS a été utilisé pour la simulation numérique des réponses de charge-tassement et les caractéristiques de transfert de charge de l'essai de charge statique traditionnel et celui d'Osterberg. La comparaison entre les calculs et les données mesurées suggère que l'essai de cellules d'Osterberg puisse être une bonne méthode pour rempalcer l'essai de charge statique traditionnel. Les différences dans des caractéristiques de transfert de charge entre le résultat de l'essai statique traditionnel et celui utilisant le cellule d'Osterberg entraine une légère augmentation de la capacité ultime de l'essai de cellules d'Osterberg.

1 INTRODUCTION

Pile load test is an effective way to verify the pile design method and evaluate the uncertainties in in-situ soil profiles and parameters. Types of pile load tests include static load test, statnamic and pseudo-static tests, Osterberg-cell test and dynamic pile test. The essential information provided by a pile load test includes the load-settlement responses, ultimate load carrying capacity, load transfer characteristics and structural integrity of a pile as constructed. The Osterberg cell (O-cell) pile load test method was developed by Osterberg (1989). By comparing the results of conventional static pile load tests with those of O-cell tests obtained from the same site, Leung and Shen (2003) established that the differences in the load transfer mechanism can be attributed to the different location and direction of the applied load between the 2 types of tests. However, despite the differences in the load transfer characteristics between the 2 types of tests, the equivalent head-down pile top load-settlement curves obtained from O-cell tests are very similar to those from conventional pile load tests, confirming the viability of the O-cell test technique.

In view of the above, a back analysis was conducted in the present study to examine the performance of an O-cell pile load test obtained from a case study in Singapore. Finite element method (FEM) using a commercial software was employed in the back analysis and the results of the back analysis are presented in this paper.

2 CASE STUDY

Two residential highrise tower blocks were constructed in the western part of Singapore. Two O-cell pile load tests were conducted on the preliminary test piles to verify the design calculations including the end bearing and shaft resistance of the pile. In this paper, the results of an O-cell test on test pile PTP1 are described and back-analyzed using FEM. The 1.2-m diameter test pile PTP1 is a cast-in-situ concrete bored pile. Figure 1 shows the details of the instrumented test pile and the O-cell assembly. The O-cell assembly made up of four 400-mm diameter O-cells was installed at 2.35 m above the pile tip. The O-cell assembly has a maximum combined test load capacity of 16.6 MN and a maximum displacement of 32.9 mm. The O-cells were pressurized using the Quick Load Test Method as given in ASTM D1143 (1978). Altogether 34 equal loading increments up to 46.88 MPa resulting in a bi-directional gross O-cell load of 16.6 MN were applied to the O-cell assembly.

Each successive load increment was held constant for 15 minutes by an automatic pressure maintenance unit that maintains the desired loading pressure. A total of 8 levels of

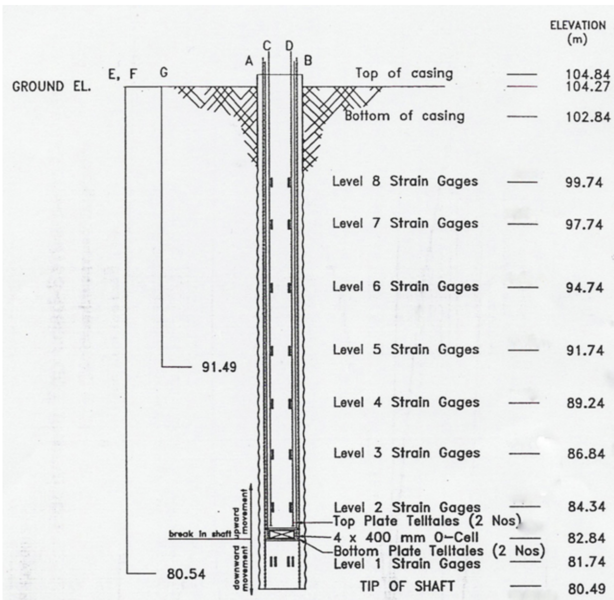

Figure 1. Instrumentation of test pile PTP1.

strain gauges(Figure1) were installed at various elevations along the test pile to monitor the load transfer characteristics during the load test. It is worthy to note that the bottom strain gauge was installed below the O-cell elevation and close to the pile tip.

Table 1: Soil Profile and Properties

Depth (up to)	Soil type	Soil properties			
		γ	E_{50}^{ref}	ν	c
m		kN/m^3	MN		
4.4	Medium clayey silt	16	5	0.35	7
6.4	Medium dense clayey silt	19	12	0.3	40
9.6	Very dense silty sand	19	27	0.25	90
12.6	Very weak siltstone fragments	20	33	0.1	110
15.0	Very dense silty sand with siltstone fragments	20	220	0.2	600
17.4	Very dense silty sand with siltstone	21	100	0.2	260
>17.4	Moderately weathered siltstone	21	180	0.2	450

The subsurfce soil profile belongs to the Jurong Formation of Singapore consisting of weak sedimentary rocks and residual soils of sedimentary origin (Leung, 1996). The soil profile and properties at the site is summarised in Table 1.

3 BACK ANALYSIS

The back analysis of the pile load test is conducted using 3-dimensional axisymmetric finite element analysis by means of the commercial computer program PLAXIS version 8.2 (2002). Undrained analysis is peformed and Mohr-Coulomb soil model with 15 node elements is adopted for the relatively stiff soils and weak rocks. Hardening-soil model is employed for the moderatey weak rocks beneath the pile tip. Figure 2 shows the finite element mesh adopted in the present study. The meshes are generated axisymmetrically with the boundary at 20 m away from the test pile to ensure minimal boundary effects on the analysis. To ensure precision in the analysis, the meshes around the test pile area are refined. The O-cell part of the pile is simulated as solid elements of about 10 cm thick in accordance with the extension range of the O-cell assembly. When the O-cell assembly is not in operation such as in the case of static load test with load applied at the pile top, the material properties of the O-cell are made identical to those of pile materials (i.e. concrete). When the O-cell is in use, its material properties are deactivated so that the interaction between the shaft upward and downward movement as well as the tip movement of the pile can be de-coupled.

The three assumptions made to reconstruct the equivalent head-down load-settlement curve at the pile top from an O-cell load test results are as follows:

- The shaft resistance-movement curve for upward movement of the pile is the same as the downward movement of a conventional head-down static pile load test.
- The end bearing load-movement curve obtained from an O-cell test is the same as the end bearing-load movement component curve of a conventional head-down test.
- The pile is assumed to be rigid so that the top and bottom have the same movement but sustaining different loads.

By adding the shaft resistance to the end bearing at the same movement, a single point on the head-down equivalent load-settlement curve can be obtained. The equivalent head-down load-settlement curve can then be determined by repeating this step to all data. If either the upper pile shaft resistance or the lower pile end bearing has reached its ultimate state before the other, hyperbolic extrapolation is usually applied by constructing the linear regression equation to fit the movement/load

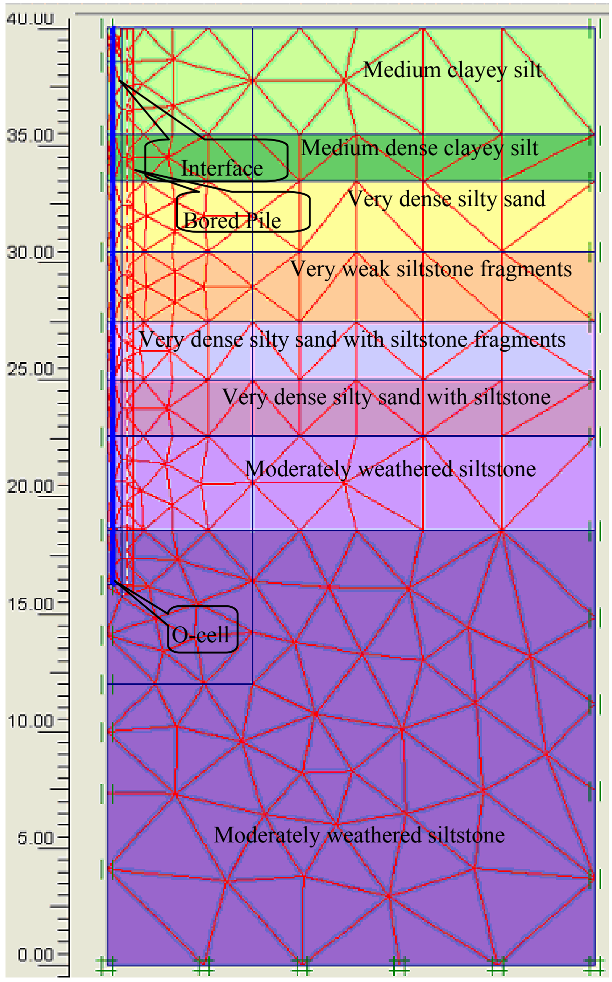

Figure 2. Finite element mesh of test pile PTP1.

versus movement curve of either component that needs to be extrapolated. In virtue of the application of finite element analysis tools, the load applied by O-cell on either component of the pile can be simulated to increase continually even if one or the other component has reached its ultimate value.

The elastic compression of the test pile can be determined accuractely based on the readings of strain gauges installed along the test pile. It is assumed that a linear distribution of load transfer exists between gauges. This is considered sufficiently accurate as there are 8 levels of strain gauges in test pile PTP1 and hence the distance between the gauges is adequately small.

4 RESULTS AND DISCUSSION

Figure 3 shows a comparison between the back-analyzed load-movement curves with the measured ones. It is noted that the FEM calculations for the upper pile portion indicate a more elastic response. This is probably attributed to the fact that Mohr-Coulomb model is applied to simulate the behaviour of the soil layer around the pile while Hardening-Soil model is applied to the soil layer below the pile toe. It is believed that a more accurate calculation can be obtained by the FEM if Hardening-Soil model is also applied to the upper soils. Unfortunately such soil model parameters are not available for the upper soils.

The observed and calculated pile load distribution curves at O-cell loads of 3.85 MN, 7.85 MN, 11.76 MN and 16.6 MN are shown in Figure 4. The comparison shows that the FEM

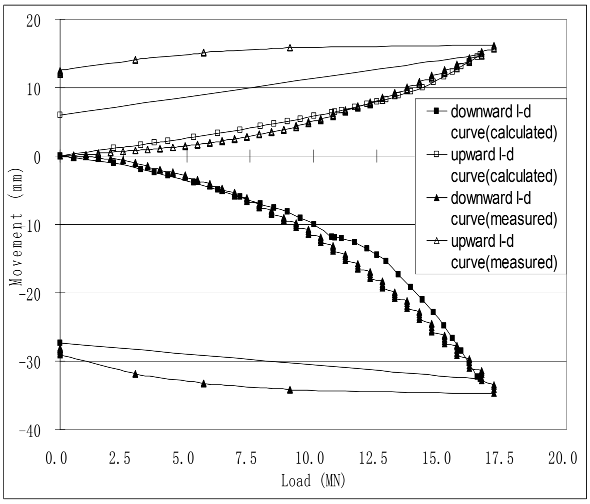

Figure 3. Comparison of load-movement curves. Curve

calculations agree well with the actual field measurements. The difference between the calculations and measurements becomes smaller when the load increases. This is considered reasonable as all the soil parameters are deduced under ultimate loading state. Again more accurate results can be achieved with a more complex soil model such as the Hardening-soil model which can capture the non-linear loading stress-strain variation.

A comparison of the calculated and measured unit shaft resistances of the test pile under O-cell load of 3.95 MN, 7.85 MN, 11.76 MN and 16.63 MN are shown in Figure 5. Again there is a close match between the 2 sets of values indicating the FEM model can achieve a satisfactory simulation of the O-cell load test data provided appropriate soil models and parameters are adopted. It is noted that the soil above Elevation (EL.) 92 m is very weak compared with the soils below. At EL. from 92 m to 89 m, there is a stiff soil layer of silty sand with siltstone fragment having standard penetration rsistance N value > 100. As expected, the very stiff soil layer below EL. 85 m provides the maximum unit shaft resistance.

It should be noted that the hyperbolic curve fit beyond the last available field test data to obtain the equation of the rendline of load-movement curve does not involve any geotechnical consideration. It is believed that using back-analyzed FEM model to fulfill the extrapolation is more rational and reasonable than the hyperbolic curve fitting. In the present case, both the components of O-cell load-movement curves are extrapolated by increasing the uplift force to 18.8 MN and the push-downward force to 18.0 MN in the FEM O-cell model.

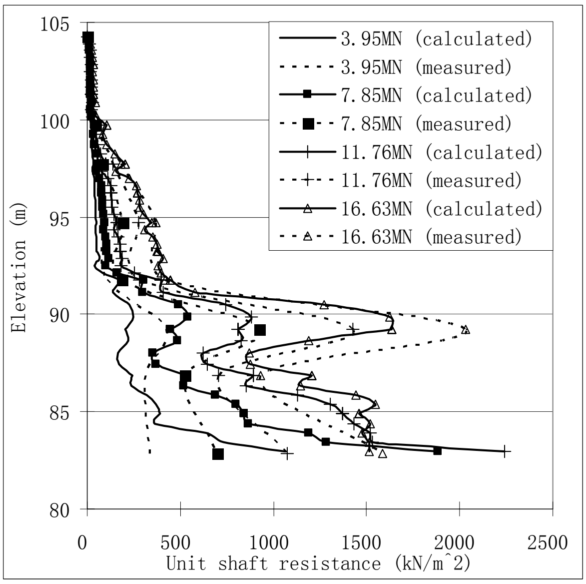

Figure 5. Comparison of unit shaft resistance curves.

The load-movement curves after extrapolation are shown in Figure 6. It can be seen that the capacity of the shaft resistance of upper part has been reached when loaded to 18.8 MN while the end bearing of lower part is still increasing at a load of 18.0 MN.

To compare the equivalency of O-cell test to conventional head-down static load test, a conventional test is simulated in the same FEM model except that the pile was loaded pushing downward from the pile head. Figure 7 shows the load-transfer curve of the conventional test together with those of calculated and measured O-cell result. Comparing those portions above the O-cell level, the similarity between the conventional test and O-cell test is evidenced by a pair of mirror images of the load-transfer curve of the two tests. Figure 8 presents the unit shaft resistance distribution for the pile as computed for the two types of tests. The shaft resistance acts in the negative direction for the O-cell test and in the positive direction for the head down test. Generally, there is very little difference between the computed unit shaft resistance values for the two types of tests.

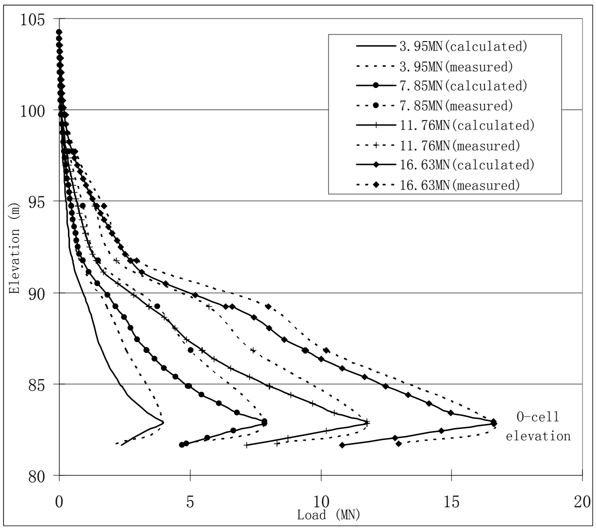

Figure 4. Comparison of pile load-distribution curves.

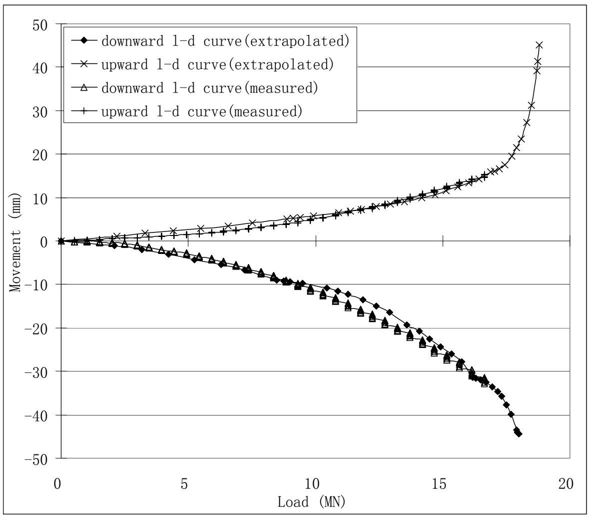

Figure 6. Extrapolation of load-movement curves by FEM.

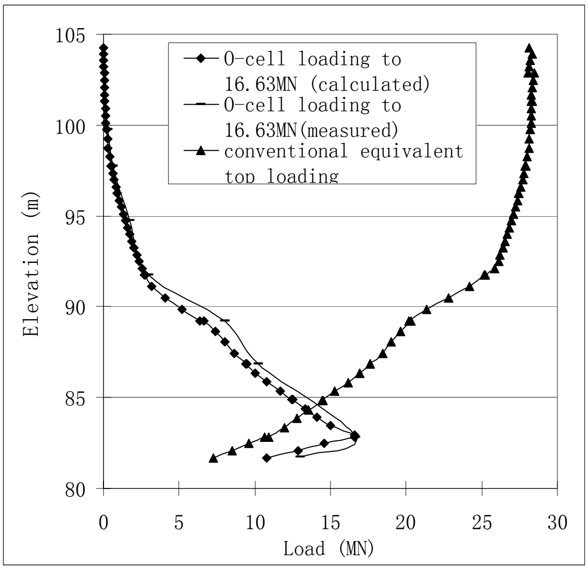

Figure 7. Comparison of load transfer curve of O-cell at 16.63MN loading with that of equivalent conventional test.

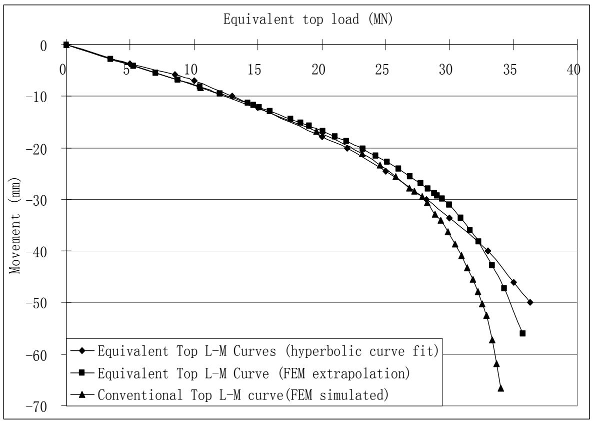

Figure 8. Comparison of unit shaft resistance curve of O-cell at 16.63MN loading with that of equivalent conventional test.

The equivalent pile top head-down load-movement curve is illustrated in Figure 9. It should be noted that while one curve is extrapolated by hyperbolic fit from the O-cell test data, the other is obtained using FEM extrapolation with PLAXIS 8. As a comparison, the FEM simulated pile top load-settlement responses is also given in the figure. The three curves almost overlap each other for pile head settlement upto 25 mm. After that, the hyperbolic curve fit method does not show a definite yield trend and gives the most stiff soil-pile interaction behavior at the end phase; while the two finite element simulations reflect a yield trend. The FEM extrapolation curve of O-cell test displays a little stiffer load-movement behaviour than that of conventional test in PLAXIS 8.

5 CONCLUSION

A back analysis has been carried out to evaluate the O-cell pile load test performance using FEM based on a case study carried out in Singapore. The following findings can be established:

- O-cell test results can provide a reasonable evaluation of soil-pile interaction and equivalent pile top load-settlement curves. As such, O-cell tests conducted on instrumented piles can determine separately the shaft resistance and end bearing components.

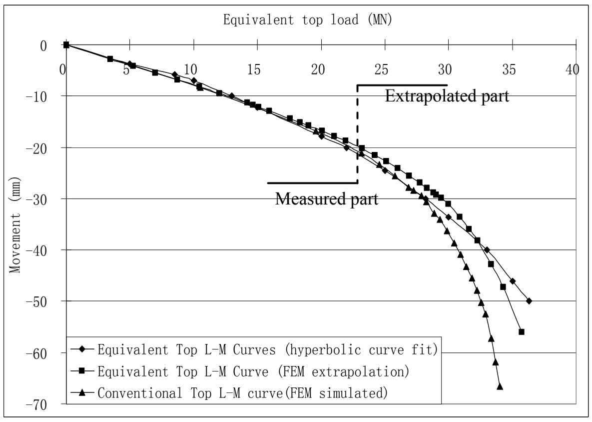

Figure 9. Equivalent top load-movement curves.

- The end bearing load-movement curve obtained from an O-cell test gives a slightly stiffer load-movement response than that of conventional test due to a shorter load transfer distance between the pile tip and the point of load application. Thus the end bearing of the O-cell test is mobilized much earlier as compared to that of conventional static pile load test.
- The equivalent pile top head-down load-movement curve of the O-cell test simulated by PLAXIS 8 gives a slightly stiffer load-movement response and higher ultimate capacity than that of conventional load test.

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