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Numerical modelling as a tool to assess empirical methods for interpreting O-cell pile load test results.

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ABSTRACT: The bidirectional (O-cell) test is a relatively new method of pile testing that is used when the test loads are high. In contrast to the single load-settlement curve resulting from the conventional (top-load) test, the results of the O-cell test consist of three separate curves. Efforts were made over the years to find a way to interpret the results of the O-cell test by transforming them to what is known as the Equivalent Top Load (ETL) curve. Many methods were proposed by different researchers to construct ETL curves. With the help of numerical modeling, this paper assessed the available empirical methods. Finite Element (FE) models were developed to simulate O-cell tests. The models were calibrated based on the data of well-documented case studies of O-cell tests. Then, the calibrated models were used to simulate the equivalent conventional tests to find their corresponding load-settlement curves. A total of seven methods for constructing ETL curves were applied to the data of the case studies to be assessed. The seven different ETL curves found from each method were compared to the load-settlement curve produced from the simulated equivalent conventional test (reference curve). The comparison was mainly based on finding errors in the values of ultimate load-carrying capacity and settlements at expected working loads estimated from each ETL curve. The results of this paper showed that the errors produced by all the available methods are significantly high. Thus, it is important to develop a new method that minimizes errors.

1 INTRODUCTION

Numerical modelling is a quite beneficial way to analyse and predict the behaviour of different structural elements since it saves time and money. In this study, numerical modelling was utilized to help in the assessment of the available empirical methods to interpret the bidirectional (O-cell) pile load test results. The O-cell test produces different results than those obtained from the conventional test. Thus, it is required to convert the O-cell test results to what is known as the Equivalent Top Load (ETL) Curve. Many researchers developed different methods to construct ETL curves.

The aim of this paper is to assess those methods with the help of numerical modelling. Finite Element (FE) models were developed and calibrated based on case studies of performed O-cell tests. Then, the equivalent conventional tests of each of the studied cases were simulated and their results were obtained. The available methods were applied to the measured results of the O-cell tests and the ETL corresponding to each method was found. To assess the methods, the ETL curves produced from all the methods were compared to the results of simulated equivalent conventional test. This paper highlights parts of the work done by Abulkhair et al. (2024).

2 BACKGROUND

During the conventional pile load test, the test pile is subjected to an increasing downward load at its top. However, in the O-cell test, the test pile is subjected to a bidirectional load induced by the O-cell, which is a jack-like device, that is placed at its bottom. The O-cell test produces three different load-displacement curves measured at the top of the pile (Q_{up}, y_1), top of the cell (Q_{up}, y_2), and bottom of the cell (Q_{down}, y_3). Those results are completely different than those measured during the conventional test, which consists of a single load-settlement curve measured at the top of the pile (Seo et al., 2016) and (Abualkhair et al.,2024).

2.1 Methods for Constructing ETL Curves

This paper assessed seven available methods for the construction of ETL curves, which are summarized in Table 1. The original method was the first developed in history by Osterberg, who was the inventor of the O-cell (Seo et al., 2016). The three main assumptions of this method were as follows:

- The compression of the pile is negligible (Seo et al., 2016).
- The skin friction resistance of the pile during an O-cell test is similar if the pile was top loaded (Seo et al., 2016).
- The end bearing resistance of the pile during an O-cell test is similar if the pile was top loaded (Seo et al., 2016).

Based on the listed assumptions the, and using the curves measured at the top and bottom of the O-cell, the ETL curve can be constructed according to the original method by summing loads at common displacements between the two curves (Seo et al., 2016).

The second two assumptions of the original method were adopted by all other methods. However, they all did not adopt the first assumption as they adjusted their methods to take the compression of the pile into account. The LOADTEST method (Method 2 in Table 1), was the first method that corrected the first assumption of the original method. It was developed by Dr. Schmertmen in 1998, and it was used by the engineers as the standard method to construct ETL curves since 2000 (Seo et al., 2016).

The other methods developed by Kwon et al. (2005), Kim and Mission (2011), Kim and Chung (2012), and Massad (2015). Also corrected for the additional compression of the pile. However, they differed in the way of estimating this additional compression.

Table 1. Assessed Methods

Method #	Method
Method 1	Original (Osterberg and Hayes, 2001)
Method 2	LOADTEST (LOADTEST, 2006)
Method 3	Kwon et al. (2005)
Method 4	Kim and Mission (2011)
Method 5	Kim and Chung (2012)- Unknown Unit Skin Friction Distribution
Method 6	Kim and Chung (2012)-Known Unit Skin Friction Distribution
Method 7	Massad (2015)

3 CASE STUDIES

Three case studies of O-cell pile load test were considered in this study. The first two cases are related to test piles OLT1 and OLT2 (Cases I and II) located in Napoli, Italy site, which were presented in detail by Russo (2013). The third case (Case III) is for a test pile located in Melak, East-Kalimantan, Indonesia, which was presented by Limas and Rahardjo (2015). For more details about soil properties and test results refer to Russo (2013) and Limas and Rahardjo (2015).

4 FINITE ELEMENT (FE) MODELLING

In this study, FE models were developed and calibrated for Cases I and II. Instead of developing and calibrating an FE model for Case III, the results of the conventional test simulated by Limas and Rahardjo (2015) were used in the assessment of the available methods for constructing ETL curves.

For Case I, an axisymmetric model was used to simulate soil-pile interaction during both the O-cell and the conventional pile load tests using MIDAS GTS NX software. The geometric properties of the FE model were selected based on a performed sensitivity analysis. The FE model developed for pile OLT1 had a width and length of 20 m and 30 m, respectively. Quadrilateral higher order elements (8-noded) are used to construct the mesh of the model. A portion of the soil zone that is adjacent to the pile was refined. The width and length of the refined zone were 10 m and 20 m, respectively. The maximum element size of the pile's mesh and the refined zone adjacent to it was 0.1m, while the rest of the mesh had a size of 0.65 m.

To simulate the O-cell during the simulation of bidirectional test, mesh elements in a 0.1 m rectangular zone in the pile at the location of the cell are deactivated. When the conventional test is simulated, the material property of this zone is set to be concrete. Boundary conditions were set to avoid the instability of the model. The horizontal displacement of the left and right sides of the mesh were constrained, while both the vertical and horizontal displacements were constrained at the bottom of the mesh. The top boundary of the mesh was set to be free to move in both x and y directions. The displacement in the x direction of the nodes on the O-cell edge was constrained during the simulation of the bidirectional test.

The Mohr-Coloumb (M-C) and linear elastic material models are assigned to the soil and concrete elements, respectively. The Mohr-Coloumb (M-C) model is the most widely used soil model in geotechnical engineering since it requires the fewest field or laboratory studies to determine its parameters. This study adopts the same parameters of the soil strata as those selected by Russo (2013). Since the axial loads carried by the pile are typically not expected to go beyond the linear elastic zone in the stress-strain behavior of the concrete in geotechnical engineering, the linear elastic model is employed to simulate the concrete.

To imitate the interaction between the soil and the pile in the models of the two simulated tests, an interface element has been incorporated. The characteristics of the soil-pile interface would have a significant impact on how the two interact. The properties of the nearby soil times a specific factor (R) yields the values of the interface properties. Table 2 provides typical (R) values. The lower (R) value is applied in the event of a layered soil profile (GTS NX: User Manual, 2020). As shown in Table 3, further selection criteria for R values based on foundation type and construction method were proposed by Kulhawy et al. (1983) and Kulhawy (1991). After performing several analyses while changing the value of R to obtain the best agreement between the predicted and measured results, an R of 0.8 yielded great matching. For Case II however, R of 0.82 yielded great matching. Clearly, those value are complying with the range of R values recommended in Table 2 and Table 3 for similar material (sand/concrete) and construction (drilled shaft built with slurry method) conditions. Figure 1 displays the mesh created for the OLT1 pile.

Table 2. Typical R Values According to Soil/Structural Element Materials (GTS NX: User Manual, 2020)

Soil Material / Structural Element Material	R
Sand/Steel	0.6-0.7
Clay/Steel	0.5
Sand/Concrete	0.8-1.0
Clay/Concrete	0.7-1.0

Table 3. R values for φ' (Kulhawy et al., 1983) and (Kulhawy, 1991)

Foundation Type and Construction Method	R value for φ'
Rough Concrete	1.0
Smooth Concrete (i.e., precast pile)	0.8-1.0
Rough Steel (i.e., step-taper pile)	0.7-0.9
Smooth Steel (i.e., pipe pile or H-pile)	0.5-0.7
Wood (i.e., timber pile)	0.8-0.9
Drilled shaft built using dry method or with temporary casing and good construction techniques	1.0
Drilled shaft built with slurry method (higher values correspond to more careful construction methods)	0.8-1.0

The at rest horizontal and vertical stresses in soil are determined before the construction of the pile. Equations 1 and 2 (Jacky, 1944) are utilized to determine the initial horizontal stress (σ'_{h0}). It should be noted that the Over Consolidation Ratio (OCR) in this study is considered to be 1. Therefore, Equation 3 can be used to calculate the coefficient of static lateral earth pressure (K_0). Test loads during the O-cell and conventional tests are applied as uniformly distributed pressure. The pressure value is calculated by dividing the load needed by the pile's cross-sectional area. A bidirectional load is applied at both the top and bottom of the cell during the O-cell test. Nevertheless, in the traditional test, the load is placed on the top of the pile. The load is applied in several increments based on the simulated case in both tests. The validity of the FE model's calibration for Case I is confirmed by the agreement between the measured curves and the ones

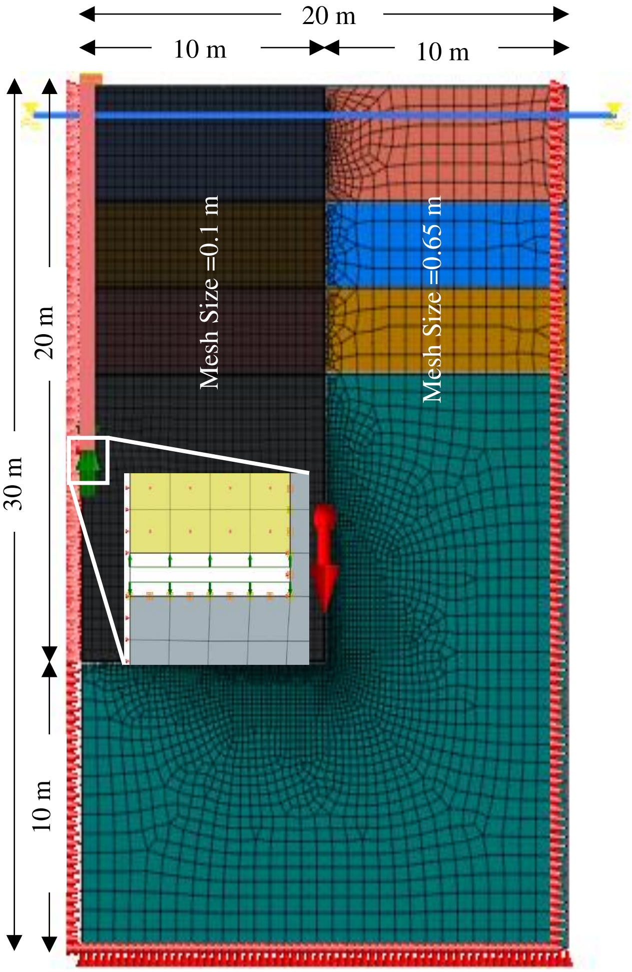

Figure 1. Developed FE model mesh for Case I (Abualkhair et al., 2024)

$$\sigma'_{h0} = K_0 \sigma'_{v0} \quad (1)$$

$$K_0 = (1 - sin\varphi')(OCR)^{sin\varphi'} \quad (2)$$

$$K_0 = 1 - sin\varphi' \quad (3)$$

derived from the model, as illustrated in Figure 2. Great agreement is also achieved for Case II.

By integrating elements' stresses at various levels along the pile, the load transfer curve is obtained. Using the properties of this calibrated model, the equivalent conventional test is simulated by applying the load at the top of the pile. The load-displacement curve of the pile's top is obtained from the simulated conventional test.

positive error in estimated settlement values implies a conservative estimation, whereas negative errors indicate non-conservative estimations. Conversely, positive errors in the estimated Q_u values imply non-conservative estimations, while negative discrepancies indicate conservative estimations.

Both AASHTO (AASHTO, 2012) and Chin (1970) techniques are utilized to predict the maximum load carrying capacity from each ETL curve.

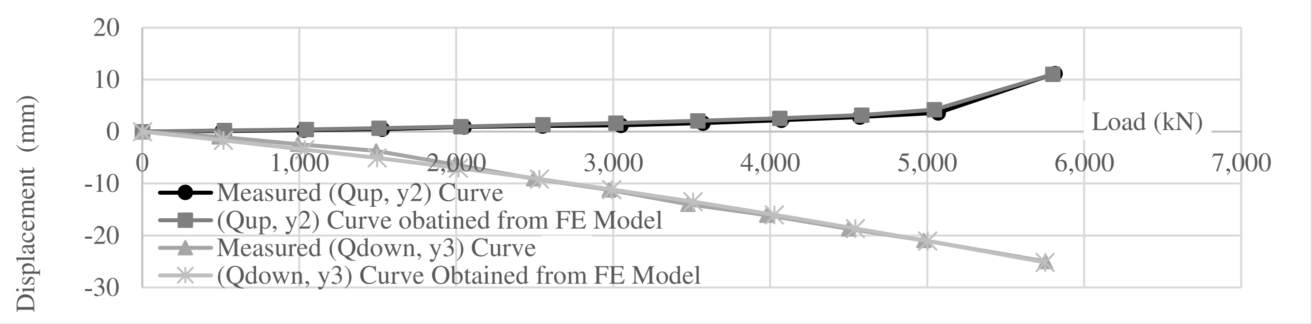

Figure 2. Measured and FE O-cell test curves for Case I

5 ASSESSMENT OF METHODS

In this part, the data from the three case studies presented in Section 3 is utilized to evaluate how well the existing empirical methods perform in creating the ETL curves. The original, LOADTEST, Kwon et al. (2005), Kim and Mission (2011), Kim and Chung (2012), and Massad (2015) methods are analysed. The evaluation concentrated on assessing the precision of the estimated ETL curve from each method. That involved determining the ultimate load carrying capacity and the settlement under working loads the curves generated by each method, then comparing them to values derived from curves produced in a simulated traditional test. The various methods are labelled as Method 1, 2, etc., as shown in Table 1.

The evaluation is conducted by determining the percentage of error in the estimated settlement or ultimate load value using Equation 4.

$$Err\% = \frac{ETL\ Value - Correct\ Value}{Correct\ Value} \times 100 \qquad (4)$$

Where "Err%" is the percentage of error (%), "ETL Value" is the estimated settlement (mm) or ultimate load value (kN) determined through empirical methods, and "Correct Value" is the settlement (mm) or ultimate load value (kN) obtained from the conventional test simulation.

It can be observed that the discrepancy between "ETL Value" and "Correct Value" was not considered in terms of absolute value, indicating that the error could be either positive or negative. In this study, a

The AASHTO method defines ultimate capacity as the load corresponding to 5%D settlement. If the load-settlement curve doesn't reach 5%D, Chin's fit is used to extend the curve and determine the load corresponding to the required settlement.

Figure 3 show the ETL curves produced by each method presented in Table 1 for Case I in comparison to the load-settlement curves obtained from the simulated equivalent conventional test. The errors in the estimated Q_u values and settlements at different expected working loads produced by all methods were found for all cases. The detailed error values (positive/negative) obtained from all cases were presented previously by Abualkhair et al. (2024). In this study, absolute average errors are presented in Section 6.

6 RESULTS AND DISCUSSION

The absolute average errors in the estimated settlements at expected working loads (S) and ultimate load carrying capacity (Q_u) produced by each method are calculated for Cases I, II, and III and summarized in Table 4, Table 5, and Table 6, respectively.

It is obvious that the order of the techniques from best to worst in predicting both (S) and Q_u values varies for each case examined. Furthermore, there was no single method that was ranked the highest in every case study. Therefore, all methods showed varying performance levels when used in different cases. Hence, in this study, the average error obtained from

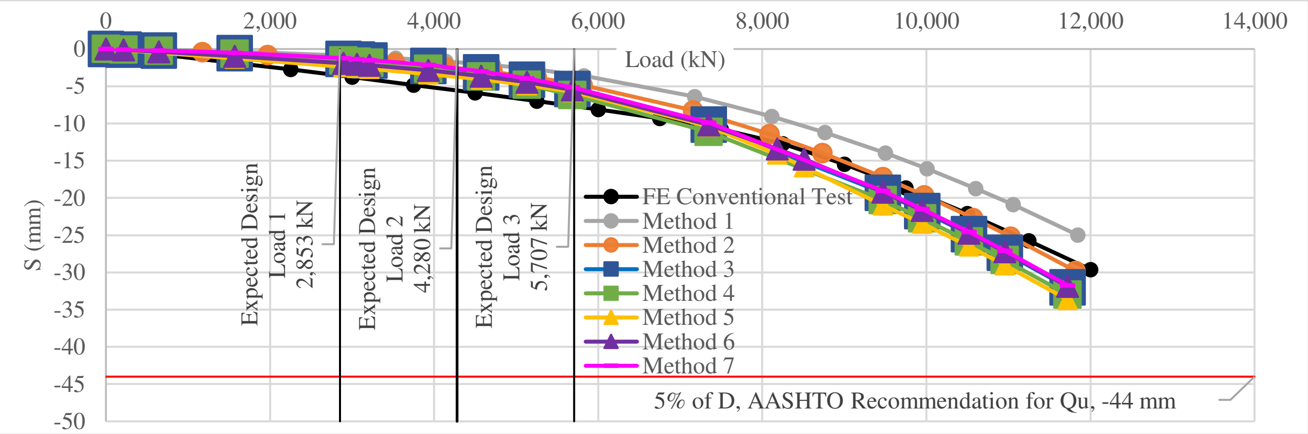

Figure 3. Assessment– Case I (Abualkhair et al., 2024)

Table 4 Average Err% - Case I (Abualkhair et al., 2024)

Method	S Err%	Qu Err%
Method 1	66	9.1
Method 2	52	8.6
Method 3	48	8.8
Method 4	40	6.8
Method 5	31	9.6
Method 6	39	8.0
Method 7	50	8.9

Table 5 Average Err% - Case II (Abualkhair et al., 2024)

Method	S Err%	Qu Err%
Method 1	75	8.0
Method 2	53	4.2
Method 3	66	5.1
Method 4	63	5.0
Method 5	18	5.3
Method 6	35	4.5
Method 7	66	5.1

Table 6 Average Err%- Case III (Abualkhair et al., 2024)

Method	S Err%	Qu Err%
Method 1	6.5	3.8
Method 2	68	7.7
Method 3	64	5.0
Method 4	64	5.0
Method 5	23	4.9
Method 6	37	1.5
Method 7	64	5.0

all cases were calculated to identify the methods with the most accurate estimation of (S) and Q_u values, which are then presented in Table 7. As indicated in Table 7, the errors in the estimated Q_u values were very similar for all the methods. Method 6 had the lowest error of 4.7%. Furthermore, the estimated settlement values had significant errors across all methods, with a range of 24% to 62%. Nevertheless, Method 5 had the lowest error (24%) in estimating settlements. Therefore, based on the mean errors identified in this research, Methods 5 and 6 demonstrated the best performance.

Table 7 Average Err% in (S) and Q_u – All Cases (Abualkhair et al., 2024)

Method	S Err%	Qu Err%
Method 1	62	7.0
Method 2	55	6.8
Method 3	58	6.3
Method 4	53	5.6
Method 5	24	6.6
Method 6	37	4.7
Method 7	59	6.3

7 CONCLUSIONS

In conclusion, this study aimed at assessing seven empirical methods for constructing Equivalent Top Load (ETL) curves from O-cell pile load test results with the help of Finite Element (FE) Modelling. FE models were developed and calibrated for two cases of O-cell test (Cases I and II in this research). The calibrated models were used to simulate the equivalent conventional tests. The FE model developed by Limas and Rahardjo (2015) for Case III was used in this study in the assessment process. The assessment was based on the error produced in the estimated ultimate load carrying capacity Q_u and settlement (S) at working loads values. The errors were found by comparing the values estimated from the ETL curves to those estimated from the load-settlement curve obtained from the simulated conventional tests. The following points were concluded:

- The ordering of the techniques in terms of accurately estimating both (S) and Q_u values varied across different cases.
- No method provided the most accurate estimations for both (S) and Q_u values in all cases examined.
- None of the methods showed consistent performance across various cases, as indicated by the two previous points.
- None of the methods could accurately estimate both (S) and Q_u values in any of the analyzed scenarios.
- Method 6 yielded the most accurate prediction of Q_u, with an average error of 4.7% across all analyzed cases. Despite not having the lowest average error, Method 2 consistently provided conservative estimates for Q_u in all cases analysed.
- Method 5 provided the most accurate predictions of (S), with an average error of 24% across all cases.
- All methods resulted in high average error rates, particularly in predicted settlements (24%-62%).

It is thought that a novel approach created through thorough statistical analysis could result in reduced errors in estimated values from an ETL curve with improved consistency across various cases.

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