Numerical Study of Cone Penetration in Clays Using Press-Replace Method

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Abstract— One of the newest numerical methods to simulate cone penetration to the soil mass is Press Replace Method (PRM). Simulations have been conducted using finite element software, PLAXIS 2D. The obtained results then compared to the measured Miniature Piezocone Penetration Test (MPCPT) data. For 6 simulations, the results show that the cone resistance predicted from the simulation is 19% lower than the measured data. Furthermore, the comparison is also conducted for excess pore water pressure at the cone face and cone shoulder (u_1 and u_2) and undrained shear strength of the soil (s_u). The results show that the predicted values are 13-22% higher than the measured values. As for undrained shear strength comparison, the result shows that the predicted values are 20% lower than the measured values.

Index Terms— Cone penetration, Undrained clay, Numerical Model

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1 INTRODUCTION

Cone Penetration Test with pore pressure measurement (CPTu) or piezocone test is one of the most versatile in-situ tests for geotechnical investigation. It is commonly used for soil type identification, soil stratification, and geotechnical parameters determination. The piezocone test is relatively fast and also it gives continuous data.

The piezocone test consists of pushing a steel cone with a measuring device attached to its tip into the ground at a constant rate of ± 20 mm/s. During the penetration, it measures the cone resistance, q_c, sleeve friction, f_s, and pore pressure, u_1 or u_2. The locations of the pore pressure measurement u_1 and u_2 are at the cone face and cone shoulder, respectively.

Unlike the laboratory testing, the measured data from the piezocone test requires interpretation to obtain soil parameters. Such interpretation requires the understanding of cone penetration process. Unfortunately, the process is a complex mechanism because it involves large deformations as soil being pushed away by a penetrating cone.

A number of finite element approaches have been proposed to analyze and interpret the cone penetration problem, namely Yu et al. 2000 (Steady State Finite Element), Lu et al. 2004 (Large Deformation Finite Element), Sheng et al. 2013 (Full-Penetration Finite Element Analysis), Ceccato and Simonini 2016 (Material Point Method). These approaches require a complex procedure to avoid numerical instabilities due to a large distortion in the soil mass.

One of the latest finite element approach to simulate cone penetration to the soil mass is Press-Replace Method (PRM). PRM originated from modeling of suction anchors (Andersen et al. 2004), and the implementation of the method was optimized and applied to installation of piles (Engin et al. 2015). Concisely, PRM is a simplified procedure that uses small-strain calculation without updating the mesh and does not consider the flow mechanism at the tip of the cone.

This paper aims to investigate the performance of Press-Replace Method (PRM) to simulate cone penetration in undrained clays. Two soil mixtures from Kurup et al. (1994) and Lim (1999) are used for analyses. The numerical results are compared with the measured data of miniature piezocone penetration tests (PCPT) in these two soil mixtures conducted at the Louisiana State University Calibration Chamber system (LSU/CALCHAS) by Tumay and de Lima (1992). The PCPT tests were performed on different stress history.

2 PRESS-REPLACE METHOD FOR CONE PENETRATION SIMULATION

In Press-Replace Method (PRM), the cone penetration problem is modeled by incrementally replacing the soil as a structural material and increasing the prescribed displacement (u_y) applied at the top. The procedure of the PRM for simulating cone penetration is shown in Fig 1.

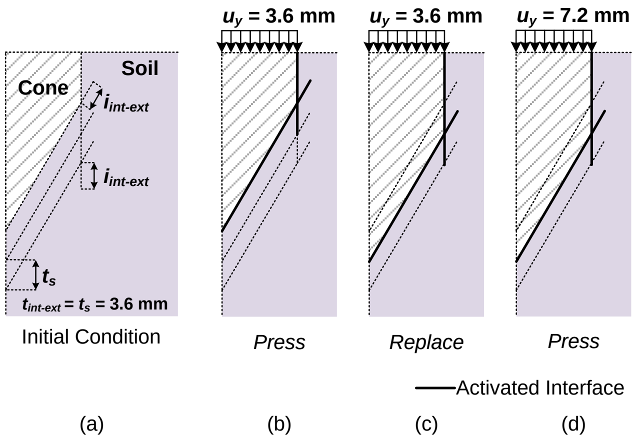

Fig. 1. PRM Steps for Cone Penetration Simulation to a depth of 0.2*D*; (a) initial phase with first replace; (b) first press; (c) second replace; (d) second press (redrawn from Lim et al. 2018)

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The initial position of the cone is defined by creating the geometrical lines. The small parts of the cone, called the *slices*, are also created. The thickness of each slice is denoted as t_s. In order to model the interaction between the cone and the soil properly, interfaces were added to these geometrical lines. As for minimizing the stress fluctuation around corners, interfaces were extended slightly to form permeable interface. The length of these interface extensions is denoted as $po_{int\text{-}ext}$. The recommended configuration of $t_s = i_{int\text{-}ext} = \Delta u_y = 0.1D$ were adopted (Engin et al. 2015).

Steps for simulating the cone penetration with PRM are as follows:

1. *Press* step, which corresponds to pressing the cone into the ground by applying prescribed displacement (u_y) vertically. During this process, the interfaces and interface extensions around the cone are activated (Fig 1 (b)).
2. *Replace* step, which corresponds to the replacement (with cone material) of the deformed soil mass due to press step. The interface between the new cone tip and the previous cone tip is then deactivated for the continuity of the cone. Interfaces and interface extensions around the new cone tip are then activated (Fig. 1 (c)).
3. Press step, which corresponds to the second press. To advance the cone to a depth of 0.2D, increase the prescribed displacement (u_y) from 3.6 mm to 7.2 mm.
4. Repeat the steps until the desired penetration depth.

3 NUMERICAL MODEL

3.1 Model Configuration and Discretization

The piezocone penetration is simulated using axisymmetric model. The configuration of the finite element model consists of cone geometry and soil layer, with an initial position of the cone embedded at depth of 5D (five times diameter of the cone). As for cone geometry, the miniature piezocone penetrometer with a cross-sectional area of 1 cm^2 and a standard cone apex angle of 60^o is modeled. As for the soil layer, it is considered as uniform soil conditions where soil weight was neglected. Fig. 2 shows the configuration of the numerical model.

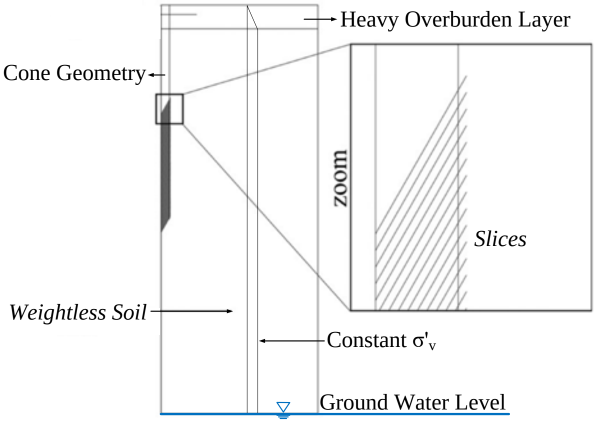

Fig. 2. Geometrical Configuration of The Finite Element Model (modified after Lim et al. 2018)

In order to create the initial stress of the soil, a thin 0.010-m layer with heavy unit weight was placed above the main soil body. The unit weight of this overburden layer is determined based on the value of the corresponding effective vertical stress. Since the soil is weightless, the overburden stresses created is constant with depth. Furthermore, in this particular study, the water level was placed at the bottom of the model. Therefore, the hydrostatic pore pressure is zero and the computed pore pressure is excess pore pressure.

After creating the geometrical lines the discretization of the model conducted by creating the 15-noded triangular elements using the *coarse* mesh setting. Fig. 3 shows the mesh refinement around slices and interfaces that were automatically generated in PLAXIS.

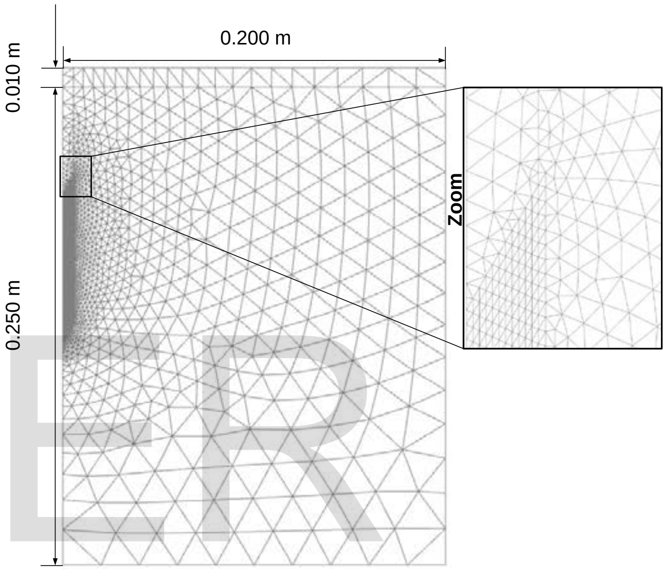

Fig. 3. Finite Element Mesh with Refinement around Slices (consists of 3364 elements, and 31011 nodes)

3.2 Obtaining Results from Press-Replace Method

Cone tip resistance (q_c) is defined as the upward vertical force acting on the cone divided by the cross-sectional of the cone. In this study, the cone penetrometer is taken weightless, and q_c values are obtained by taking the stresses across the top of the cone, as shown in Fig. 4. As the cone advanced through the replace step, the stresses were then taken across the updated positions of the cone. The location of pore-water measurement, both u_1, and u_2, are also indicated in Fig. 4.

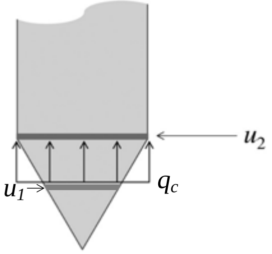

Fig. 4. Cone Resistance and Pore Pressure Location as found in PRM

Another important parameter that can be predicted from the numerical results is undrained shear strength. The value of cone factor, N_k is used to estimate the undrained shear strength of the soil. The cone tip factor, N_k is defined as:

$$N_K = \frac{q_c - \sigma_{vo}}{S_u} \qquad (1)$$

4 SOIL PARAMETERS

In this study, the Modified Cam-Clay (MCC) model is used to describe the behavior of clayey soil. Two soil mixtures, namely K_{50} soil and K_{33} soil from Kurup et al. (1994) and Lim (1999) are used for analysis. Table 1 presents a summary of the two soil mixtures parameters derived by Abu-Farsakh et al. (2003).

TABLE 1
MATERIALS PARAMETERS USED FOR MODIFIED CAM-CLAY MODEL
(AFTER ABU-FARSAKH ET AL. (2003))

Parameter	Symbol	Soil Type	
		K_{50}	K_{33}
Slope of virgin consolidation line (-)	λ	0.11	0.06
Slope of unloading-reloading (-)	κ	0.024	0.01
Slope of Critical State Line (-)	M	1.20	1.00
Coefficient of hydraulic conductivity (m/s)	k	0.5×10^{-9}	0.5×10^{-9}
Initial void ratio* (-)	e_o	1.00	1.00
Poisson's ratio (-)	ν	0.30	0.30

*assumed

The K_{50} soil specimens were prepared by mixing 50% kaolinite and 50% fine sand (by weight), while the K_{33} soil specimens were prepared by mixing 33% kaolinite and 67% fine sand. Miniature piezocone penetration testing (MPCPT) was conducted on these two types of soil specimens. The specimens are consolidated against backpressure of 138 kPa. For further details on specimen preparation, one can refer to Voyiadjis et al. (1993). Full details of the test procedure can be found in Kurup et al. (1994) and Lim (1999). Table 2 presents a summary of the stress history of the soil specimens tested in the calibration chamber.

TABLE 2
SUMMARY OF STRESS HISTORY OF SOIL SPECIMENS
(AFTER ABU-FARSAKH ET AL. (2003))

Specimen number	Soil type	Chamber consolidation	OCR	Final effective stress (kPa)		Lateral stress coefficient (k_o)
				Vertical	Horizontal	
1*	K_{50}	Isotropic	1	207.0	207.0	1.00
2*	K_{50}	k_o-anisotropic	1	207.0	107.6	0.52
3**	K_{33}	Isotropic	1	207.0	207.0	1.00
4**	K_{33}	k_o-anisotropic	1	262.0	86.2	0.42
5**	K_{33}	Isotropic	1	262.2	262.2	1.00
6**	K_{33}	k_o-anisotropic	1	262.2	104.8	0.40

*From Kurup et al. (1994)

**From Lim (1999)

As for the undrained shear strength comparison, Abu-Farsakh et al. (2003) provided the cone tip factor (N_k) and measured undrained shear strength data. The calculated cone tip factor is based on their investigations, which the cone tip factor is the function of the rigidity index (I_r) and stress factor (Δ). Table 3 shows the cone tip factor and measured undrained shear strength for the six specimens.

TABLE 3
MEASURED UNDRAINED SHEAR STRENGTH
(AFTER ABU-FARSAKH ET AL. (2003))

Specimen	Rigidity Index, $I_r = G/S_u$	Cone Tip Factor, N_k	Measured S_u (kPa)
1	167	12.5	60
2	150	11.47	65
3	100	10.74	80
4	333	11.41	85
5	167	11.66	98
6	400	11.87	121

5 ANALYSIS AND RESULTS

The analysis was carried out to analyze the miniature piezocone penetration measurement in terms of cone resistance, q_c, and excess pore pressure both at cone face and cone shoulder (u_1 and u_2). These predicted values obtained during miniature piezocone penetration using PRM are compared with experimental values obtained at the steady state during the MPCPT tests conducted in the calibration chamber. Furthermore, a comparison of undrained shear strength is also conducted based on measured undrained shear strength data provided by Abu-Farsakh et al. (2003).

In Press-Replace Method, steady-state was reached approximately at a penetration depth of 3.5*D*. As for greater penetration depths, the increase of cone resistance value is relatively small. Fig. 5 shows the distribution of cone resistance with normalized penetration depth for specimen 2.

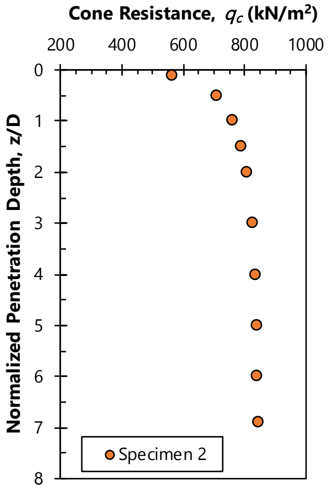

Fig. 5. Distribution of Cone Resistance with Normalized Penetration Depth (Specimen 2, k_o = 0.52)

TABLE 4

COMPARISON BETWEEN MEASURED AND PREDICTED RESULTS AT STEADY-STATE CONDITION

Specimen	**Cone Resistance, q_c (kPa)**			**Excess pore pressure (kPa)**					
				at cone face, u_1			**at cone shoulder, u_2**		
	Predicted	**Experiment**	**Differential (%)**	**Predicted**	**Experiment**	**Differential (%)**	**Predicted**	**Experiment**	**Differential (%)**
1	1065.0	1196	11.0	744	562	32.4	660	580	13.8
2	845.7	822	2.9	567	410	38.3	360	360	0.0
3	1030.4	1224	15.8	752	649	15.9	578	418	38.3
4	936.8	1161	19.3	647	467	38.5	450	483	6.8
5	1303.8	1489	12.4	952	794	19.9	711	779	8.7
6	911.1	1408	35.3	760	535	42.1	797	523	52.4

Table 4 shows the complete comparison between the calculated and the measured cone tip resistance, q_c, and the excess pore pressures at the cone face (u_1) and cone shoulder (u_2).

4.1 Cone Resistance Comparison

For all six simulations, the predicted values of cone resistance are lower than the measured values. Based on linear regression, the predicted values are approximately 19% lower than the measured values. Fig. 6 shows the cone resistance comparison.

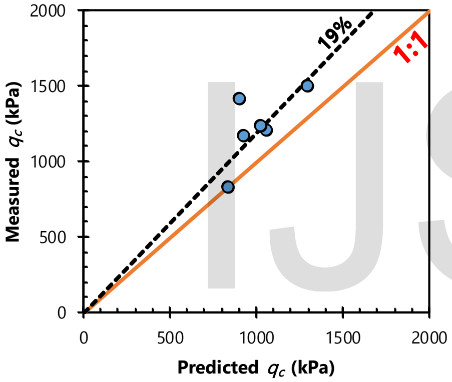

Fig. 6. Predicted versus measured cone resistance, q_c

4.2 Excess Pore Pressure Comparison

As for the excess pore pressure, the comparison is conducted for both u_1 and u_2. The predicted values of u_1 give 22% higher values than the measured values.

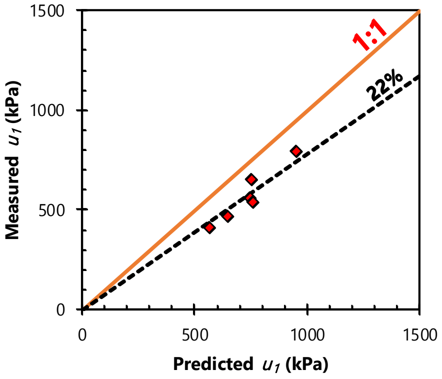

Fig. 7. Predicted versus measured pore pressure at cone face, u_1

While for u_2, the predicted values give 13% higher than the measured values. Fig. 7 and Fig. 8 show the excess pore pressure comparison.

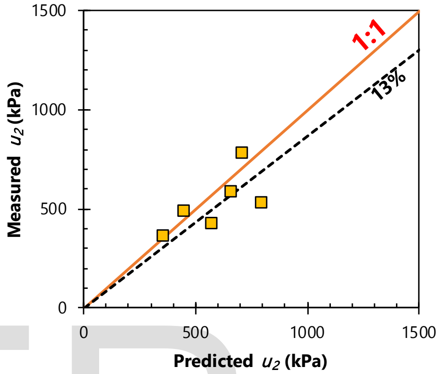

Fig. 8. Predicted versus measured pore pressure at cone shoulder, u_2

4.3 Undrained Shear Strength Comparison

Undrained shear strength is calculated using equation 1 for all six simulations. The result shows that the predicted values are 20% lower than the measured values. Fig. 9 shows the undrained shear strength comparison.

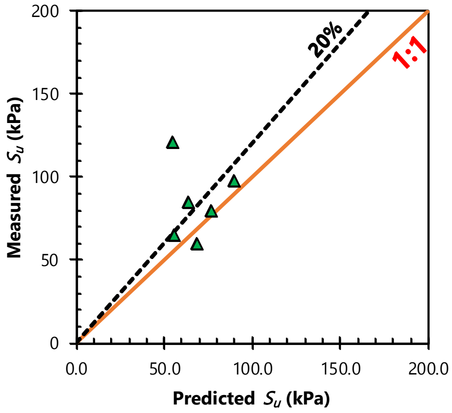

Fig. 9. Predicted versus measured undrained shear strength, S_u

5 CONCLUSIONS

Press-Replace Method (PRM) is one of the latest numerical approaches for simulating a cone penetration problem. PRM is a simplified method to simulate deep penetration, with a relatively simple procedure compared to available other methods. Furthermore, simulation using PRM can be conducted in a faster time and with reasonable accuracy.

Comparison between the predicted values obtained from PRM and measured values have been presented. The results show that for cone resistance, the predicted values are 19% lower than the measured values. As for excess pore pressure comparison at the cone face (u_1) and cone shoulder (u_2), the predicted values are higher 22% and 13%, respectively. The undrained shear strength comparison also gives an acceptable accuracy, with an average differential of 20%.

REFERENCES

[1] Ceccato, F., and Simonini, P. (2017). “Numerical Study of Partially Drained Penetration and Pore Pressure Dissipation in Piezocone Test”. Acta Geotechnica. 12:195-209 DOI 10.1007/s11440-016-0448-6.

[2] Sheng, D., Cui, L., and Ansari, Y. (2013). “Interpretation of Cone Factor in Undrained Soils via Full-Penetration Finite-Element Analysis”. International Journal of Geomechanics. 2013.13:745-53.

[3] Lu, Q., Hu, Y., Randolph, M. F., and Bugarski, I. C. (2004). “A Numerical Study of Cone Penetration in Clay.” Geotechnique, 54(4), 257–267.

[4] Yu, H. S., Herrmann, L. R., and Boulanger, R. W. (2000). “Analysis of Steady Cone Penetration in Clay.” J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)1090-0241(2000)126:7(594), 594–605.

[5] Andersen, K. H., Andresen, L., Jostad, H. P., and Clukey, E. C. (2004). “Effect of skirt-tip geometry on set-up outside suction anchors in soft clay.” Proc., 23rd Int. Conf. on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers, New York, 1035–1044.

[6] Engin, H. K., Brinkgreve, R. B. J., and van Tol, A. F. (2015). “Simplified numerical modeling of pile penetration—The press-replace technique”. International Journal of Numerical and Analytical Methods in Geomechanics. 39(15), 1713–1734.

[7] Engin, H.K., (2013). “Modeling Pile Installation Effects – A Numerical Approach”, Ph.D. Thesis. Delft University of Technology, Delft, Netherlands.

[8] Kurup, P. U., Voyiadjis, G. Z., and Tumay, M. T. (1994). ‘‘Calibration chamber studies of piezocone test in cohesive soils.’’ J. Geotech. Eng., 120(1), 81–107.

[9] Lim, B. (1999). ‘‘Determination of consolidation characteristics in fine soils evaluated by piezocone tests.’’ Ph.D. thesis, Dept. of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, La.

[10] Tumay, M. T., and de Lima, D. C. (1992). ‘‘Calibration and implementation of miniature electric cone penetrometer and development, fabrication, and verification of the LSU in-situ testing calibration chamber (LSU/CALCHAS).’’ LTRC/FHWA Rep. No. GE-92/08, Federal Highway Administration, Washington, D.C.

[11] Abu-Farsakh, M., Tumay, M., and Voyiadjis, G. (2003). “Numerical Parametric Study of Piezocone Penetration Test in Clays”. International Journal of Geomechanics. 3. 10.1061/(ASCE)1532-3641(2003)3:2(170).

[12] PLAXIS 2D Software. (2018). Material Models Manual. Plaxis BV, Netherlands.

[13] Lim, Y.X., Tan, S.A., and Phoon, K.K. (2018). “Application of Press-Replace Method to Simulate Undrained Cone Penetration”. International Journal of Geomechanics., 10.1061/(ASCE)GM.1943-5622.0001186.

[14] Lim, Y.X. (2017). “Numerical Study of Cone Penetration Test in Clays Using Press-Replace Method”. Ph.D. Thesis. Department of Civil and Environmental Engineering. National University of Singapore.