IOP Conf. Series: Earth and Environmental Science **153** (2018) 052054 doi:10.1088/1755-1315/153/5/052054

Application of the Coupled Eulerian-Lagrangian finite element method on piezocone penetration test in clays

Sen ZHANG, Jiang Tao YI

School of Civil Engineering, Chongqing University, Chongqing 400044, China

Email: fghlzz@126.com

Abstract. This paper proposed a Coupled Eulerian-Lagrangian (CEL) finite element model to estimate the undrained piezocone resistance and penetration pore pressure in modified Cam clay (MCC). The numerical model is verified through comparison with a series of miniature piezocone penetration test in calibration chamber. The value of cone tip resistance (qc), excess pore pressure at cone face (u1) and cone shoulder (u2) obtained from CEL model are also compared with the analytic closed-form solution of cavity expansion. Consequently, the value of qc is underpredicted by cavity expansion approach, but the predicted value of excess pore pressure for ordinary consolidated clays is in fairly good agreement with the value CEL modeled.

1 Introduction

The piezocone penetration test (CPTU) is used in geotechnical engineering to estimate relevant material properties in soils and be widely recognized as a fast economical in situ test. The value of cone resistance (q_c), excess pore pressure at cone face (u1) and the cone shoulder (u2) can be measured by piezocone. Many approaches have been proposed to estimate these measurements including bearing capacity theories, cavity expansion theories, and finite element method. There are many different kinds of finite element model to be used in simulating the process of piezocone penetration into clay [1] [2], one of the most common is the classical Lagrangian finite element model. Qiu [3] [4] developed a Coupled Eulerian-Lagrangian (CEL) finite element model to simulate deep penetration. The result from the new approach is in good agreement with the classical finite element analysis. Qiu also suggested that CEL can combine the advantages of Lagrangian and Eulerian formulation, and be more suitable to deal with deep penrtration problems than purely Lagrangian formulation. Therefore, this paper proposed a CEL model in ABAQUS to simulate the piezocone penetration test.

2 CEL Model

To directly verify the results from CEL model, the miniature piezocone penetration test in the calibration chamber conducted by Kurup [5] is analyzed. This analysis simulated a piezocone being penetrated into homogeneous clay in undrained condition. The proposed numerical model adopts the prototype size in the test. The piezocone is modeled with cross-sectional areas of 1 cm^2 and a standard cone apex angle of 60^0. The height of the soil domain is 300mm and the radius is 150mm.

The three-dimensional CEL model applying in this paper is presented in Figure 1. The piezocone is modeled as a discrete rigid body with Lagrangian mesh which is located at the ground level in the beginning. The piezocone is supposed to penetrate into the soil domain until the length of 150mm (about 25 radii) which is deep enough to reach steady state.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

IOP Conf. Series: Earth and Environmental Science **153** (2018) 052054 doi:10.1088/1755-1315/153/5/052054

A quarter of a cylindrical soil body is modeled since the axisymmetry of the piezocone penetration problem. The soil body is discretized into 115200 EC3D8R Eulerian brick elements. The smallest dimension of the Eulerian element is 0.7mm. There is a void layer at the top 20mm of the soil domain in the beginning. As the penetration of piezocone, the soil can flow into this area. The initial condition of the CEL model is according to the CPTU test in the calibration chamber.

Table 1 material parameters for k50 soil

Parameter	Value	Description
λ	0.11	Slope of the normal compression line in e-lnP space
κ	0.024	Slope of the unloading-reloading line in e-lnP space
M	1.2	Slope of the critical state line
Γ	1.162	Intercept of CSL
ν	0.3	Poisson's ratio

The contact in this simulation is modeled as a general contact with penalty approach. The friction angle is assumed to be zero. This simplification is also adopted by Qiu, the relevant effects on numerical results of piezocone penetration test is small.

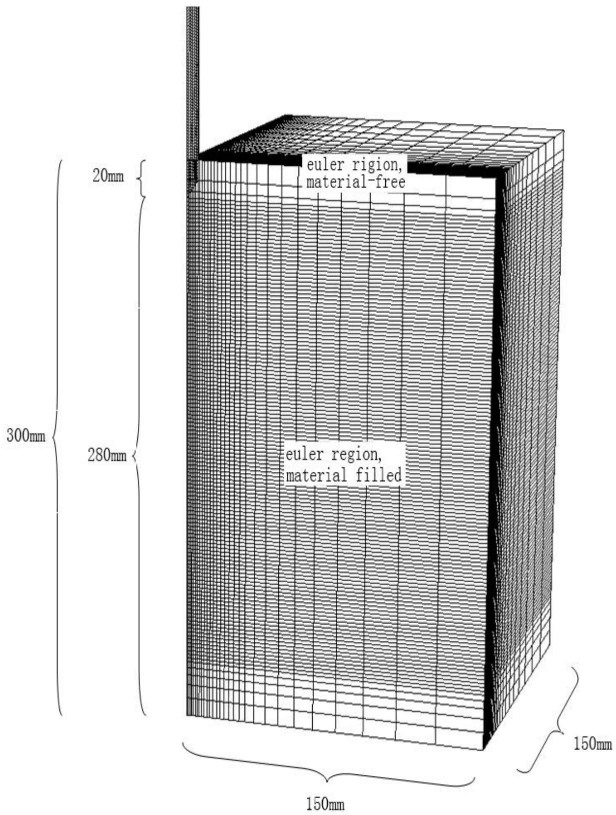

Figure 1 Geometry and Eulerian mesh of the three-dimensional model

3 Test Parameter

According to Kurup [5], the k50 soil was prepared in two steps: first, the soil was consolidated in a consolidometer. Then it was reconsolidated in the calibration chamber. In this paper, we adopt the modified Cam clay (MCC) model to simulate k50 soil and the details of the parameters are shown in

Table 1. There are three specimens (1, 2, and 3) of k50 soil to be simulated in accordance with the calibration chamber tests. The summary of soil specimens are shown in Table 2.

Table 2 summary of stress history of soil specimens

Specimen number	Soil type	Chamber consolidation	OCR	Final effective Stress(KPa)		Lateral Stress Coefficient (k_0)
				vertical	horizontal	
1	K_{50}	Isotropic	1	207.0	207.0	1.00
2	K_{50}	Isotropic	5	41.5	41.5	1.00
3	K_{50}	Anisotropic	1	207.0	107.6	0.52

4 Results

The value of cone resistance (q_c) and excess pore pressures at tip (u1) and the shoulder (u2) obtained from the proposed model is compared with the measured data. The cone tip resistance profile for the specimen 1 is presented in Figure 2. Figure 3 shows the excess pore pressures profile for soil specimen 1 at steady state. The value of excess pore pressure at the cone face and shoulder are calculated from the closest point to the according position. The comparison of the q_c value between the modeled and the measured for three specimens are presented in Table 3. The comparison of excess pore pressure value about u1, u2 are shown in Table 4, 5. There is a good agreement between the value CEL modeled and measured data.

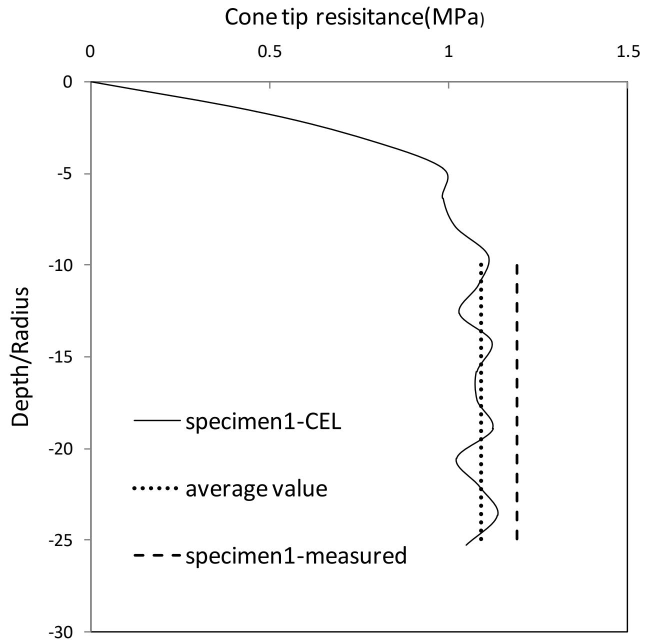

Figure 2 Measured versus calculated cone tip resistance profile for specimen 1

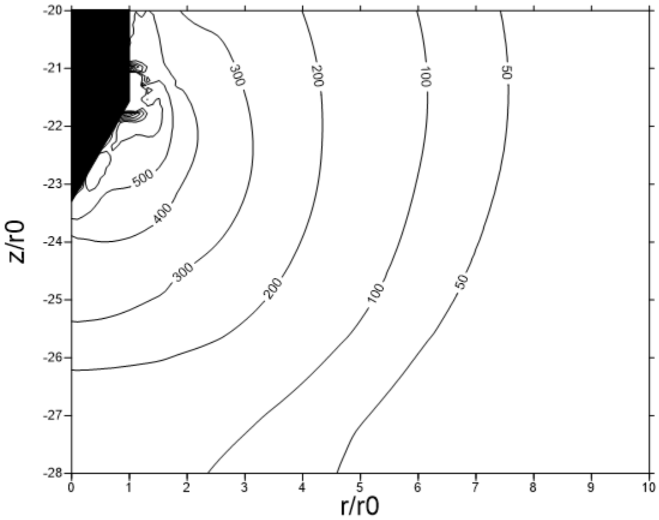

Figure 3 Contours of excess pore pressure (KPa) for specimen 1 at steady state

Table 3 Comparison of q_c between Measured, CEL Modeled and Cavity expansion

Specimen number	q_c (MPa)		
	Experiment	CEL	Cavity expansion
1	1.19	1.09	0.74
2	0.63	0.56	0.33
3	0.69	0.73	0.58

5 Compared with cavity expansion

As reviewed by Yu [6], the influences of soil stiffness and compressibility can be considered by the cavity expansion approach. Cavity expansion solution can provide a more accurate prediction than the bearing capacity theory. Thus, combining different soil models with cavity expansion is widely used in the interpretation of piezocone test [7] [8] [9]. In order to interpret the link between the cavity expansion solution and the process of piezocone penetration, the value CEL modeled is also compared with the analytic closed-form solution of cavity expansion. According to Chang [7], it is commonly accepted to use the spherical cavity expansion to estimate the excess pore pressure at cone face (u1) and piezocone resistance (q_c). According equations are expressed as

$$q_c = \frac{2}{3}Mp_0'\left(\frac{R}{2}\right)^{\wedge}\left[\ln\left(\frac{2G}{Mp_0'(R/2)^{\wedge}}\right) + 1\right] + P_0 \quad (1)$$

$$u_1 = \frac{2}{3}Mp_0'\left(\frac{R}{2}\right)^{\wedge}\ln\left(\frac{2G}{Mp_0'(R/2)^{\wedge}}\right) + p_0'\left(1 - \left(\frac{R}{2}\right)^{\wedge}\right) \quad (2)$$

The cylindrical cavity expansion solution is used to predict the value of pore pressure at cone shoulder (u2) and the prediction is shown as

$$u_2 = \frac{Mp_0'}{\sqrt{3}}\left(\frac{R}{2}\right)^{\wedge}\ln\left(\frac{G\sqrt{3}}{Mp_0'(R/2)^{\wedge}}\right) + p_0'\left(1 - \left(\frac{R}{2}\right)^{\wedge}\right) \quad (3)$$

For further details on equations, one can refer to Cao [10]. The comparison of q_c, u1, u2 between Measured, CEL Modeled and Cavity expansion solution is also presented in Table 3, 4, 5 respectively. The distribution of excess pore pressure at shoulder position with radial distance for specimen 1 is shown in Figure 4.

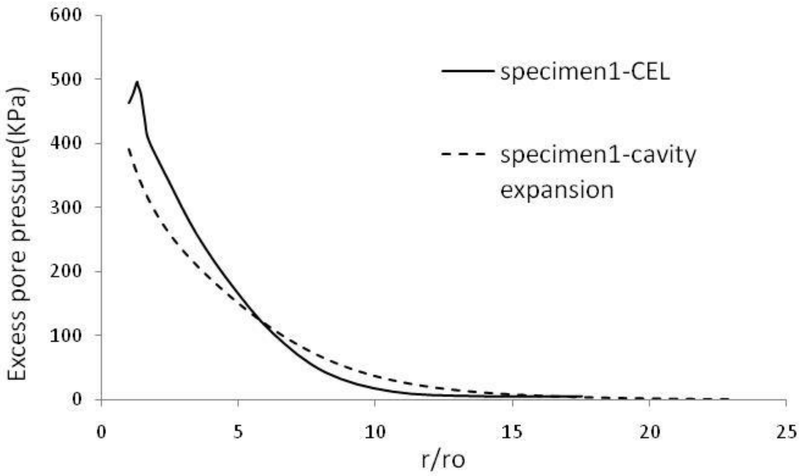

Figure 4 Comparison of excess pore pressure with radial distance for specimen 1

Table 4 Comparison of U1 between Measured, CEL Modeled and Cavity expansion

Specimen number	u1 (KPa)		
	Experiment	CEL	Cavity expansion
1	562	589	519
2	480	387	178
3	410	444	391

Table 5 Comparison of U2 between Measured, CEL Modeled and Cavity expansion

Specimen number	u2 (KPa)		
	Experiment	CEL	Cavity expansion
1	580	517	449
2	390	317	140
3	360	332	333

Consequently, the cavity expansion approach provides underpredicted value about q_c, that may because the cavity expansion solution only can consider the deformation of the soil at radial direction. Actually, the deformation of the soil in vicinity of the piezocone tip is spatially two-dimensional. The predicted value of excess pore pressure for ordinary consolidated clays is in fairly good agreement with the value CEL modeled.

6 Conclusion

In this paper, we have proposed a Coupled Eulerian-Lagrangian (CEL) model to simulate the piezocone penetration test. The value of cone tip resistance (q_c) and the associated excess pore pressures at tip (u1) and the shoulder (u2) obtained from the proposed model are compared with the test measured data and analytic closed-form solution of cavity expansion. The results show a good agreement and the CEL model is verified to generate reliable information about cone tip resistance and penetration pore pressure in modified Cam clay (MCC) at undrained condition.

References

[1] Abu-Farsakh, M, Tumay, M &Voyiadjis, G. Numerical parametric study of piezocone penetration test in clays[J].Int J Geomech, 2003; 3(2): 170–181.
[2] D Sheng, L Cui, Y Ansari. Interpretation of Cone Factor in Undrained Soils via Full-Penetration Finite-Element Analysis [J]. International Journal of Geomechanics, 2013; 13 (6): 745–753.

[3] Qiu G, Henke S, Grabe J. Application of a coupled Eulerian-Lagrangian approach on geomechanical problems involving large deformations [J]. ComputGeotech, 2011, 38(1):30-9
[4] Henke S, Qiu G, Grabe J. Application of a Coupled Eulerian–Lagrangian approach on pile installation problems under partially drained conditions [J]. ComputGeotech, 2015, 63: 279-290
[5] Kurup, P U, Voyiadjis, G Z, and Tumay, M T. Calibration chamber studies of piezocone test in cohesive soils[J]. Geotech.Eng, 1994, 120(1): 81–107.
[6] Yu, H S, Mitchell, J K. Analysis of cone resistance: Review of methods [J]. Geotech. and Geoenvir. Engrg, 1998, 124(2): 140-149.
[7] Chang MF, Cao LF, The CI. Undrained cavity expansion in modified Cam clay. II: Application to the interpretation of cone penetration tests [J]. Geotechniquem, 2001, 51(4): 331–346.
[8] Y Zhang, J Li, F Liang, J Tang. Interpretation of cone resistance and pore-water pressure in clay with a modified spherical cavity expansion solution [J].Bull EngGeol Environ, 2015, 75(1): 1–9.
[9] J Chai, MJ Hossain, DJ yuan, S Shen, JP Carter. Pore pressures induced by piezocone penetration [J].Can.Geotech, 2015, 53
[10] Cao LF, Teh CI, Chang MF. Undrained cavity expansion in modified Cam clay. I: Theoretical analysis [J]. Geotechnique, 2001, 51(4): 323–334.