Mohapatra, Debasis; Mohammadi Hasanbarough, Saeideh; Saresma, Maarit; Virtasalo, Joonas; Sołowski, Wojciech Tomasz

Numerical simulation of in-situ free fall cone penetrometer tests using the material point method

Published in:
UK Association for Computational Mechanics

Published: 12/04/2024

Numerical simulation of in-situ free fall cone penetrometer tests using the material point method

Debasis Mohapatra [1*], Saeideh Mohammadi[1], Maarit Saaresma[2], Joonas Virtasalo[2], Wojciech Sołowski[1]

Department of Civil Engineering, Aalto University, Espoo, Finland.
debasis.mohapatra@aalto.fi, wojciech.solowski@aalto.fi
[2]Geological Survey of Finland, Espoo, Finland
maarit.saresma@gtk.fi, joonas.virtasalo@gtk.fi

Abstract

This paper proposes a numerical framework to simulate in-situ free fall cone penetration tests conducted on soft and sensitive marine clay. First, the free fall cone penetration tests are carried out at an offshore site in the northern part of the Gulf of Finland, Baltic Sea. The numerical simulation employs the Generalized Interpolation Material Point Method to replicate the process of indentation of the cone penetrometer into the clay. The clay is modelled using an advanced constitutive model that considers the effect of strain rate and strain softening associated with the dynamic penetration process. The simulation uses a friction contact model to represent the interface between the cone penetrometer and the clay. The numerical simulation accurately replicates the penetration process associated with the tests.

Keywords: *Free fall cone penetrometer test, Generalized Interpolation Material Point Method, Contact Problems, Strain rate, Destructuration.*

1 Introduction

The free fall cone penetrometer tests (FF-CPT) are simple, rapid, and cost-effective tests often used in seabed characterization [1]. However, there are still uncertainties in the interpretation of the test data and its correlation with the soil properties. Currently, the correlations used are largely empirical and analytical [2–4], primarily due to the complexities associated with numerically simulating the dynamic penetration process. Therefore, the development of reliable numerical models capable of replicating the dynamic penetration process may lead to more accurate correlations and data interpretation, thereby enhancing the precision of soil properties obtained with FF-CPT.

The experimental [3,5] and numerical studies [6,7] point out that the uncertainties in FF-CPT data interpretation could be due to the wide range of strain rates associated with the test. However, the determination of the strain rate effect on the shear strength of soil is quite complicated due to its possible dependency on soil properties, cone penetrometer parameters (e.g., geometry, density), and impact velocity. Further, the marine clays are also sensitive, and their undrained shear strength reduces during the cone penetration process due to the destructuration of clay. Not considering the effects of strain rate and destructuration on clay will significantly influence the accuracy of the numerical simulation.

In the present study, we replicate an in-situ free fall cone penetrometer test results with the Generalized Interpolation Material Point Method simulation. The numerical simulation results that consider the effect of strain rate and destructuration of clay well replicate the dynamic penetration process.

2 Problem description

The study area is situated to the south of Kytö Island in the Gulf of Finland, north of the Baltic Sea. Three FF-CPT tests were conducted at this location using the Graviprobe 2.0 (@dotOcean). The Graviprobe free fall penetrometer (FFP) has a length of 1.97 meters, weighs 20.2 kilograms, and has a diameter of 0.05 meters. The Graviprobe is dropped from the sea surface, and it accelerate in free fall and penetrates into the seabed with an impact velocity of approximately 7.6 m/s. The variation of acceleration with depth associated with the three different FF-CPT experiments is shown in Figure 2. Triaxial tests carried out on soil samples collected from the location suggest that the undrained shear strength of the soil sample varies between 6-7 kPa.

This paper uses Generalized Interpolation Material Point Method (GIMP) as encoded in Uintah software (http://uintah.utah.edu/) for numerical simulation of the FF-CPT. The numerical geometry of the model is defined by taking advantage of the axisymmetric condition of the test (Figure 1). The lateral and vertical spread of the soil domain is decided based on a few trial analyses, so that the boundaries will not influence the outcome of the numerical simulation. The dimensions of free fall penetrometer are consistent with the Graviprobe dimensions used in the experiment. For numerical modelling, the domain is discretized by using a structured mesh of square size (5mm× 5mm) with 4 material points in the cell. These corresponds to 10364 number of material points in the simulation. The simulations assume frictional contact with friction coefficient (μ), implemented in Uintah by [8]. The simulation uses a more recent friction contact algorithm , which uses logistic regression to identify the interface between two materials in contact.

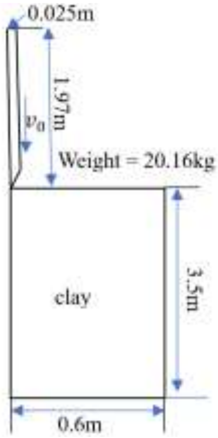


Figure 1. Numerical model of FF-CPT. Unit: m

The simulation uses the Tresca material model extended to consider the effect of strain rate and destructuration on undrained shear strength as mentioned in [9,10]. The undrained shear strength of clay is expressed as a function of strain rate ($\delta\gamma$), accumulated shear strain (ξ), and sensitivity (S_t) as:

$$s_u(\delta\gamma, \xi, S_t) = s_{u,ref}\left[\left(\frac{\delta\gamma}{\delta\gamma_{ref}}\right)^{\beta}\right]\left[\frac{1}{S_t} + \left(1 - \frac{1}{S_t}\right)e^{\frac{-3\xi}{\xi_{95}}}\right] \quad (1)$$

where $s_{u,ref}$ is reference shear strain at reference strain rate ($\delta\gamma_{ref}$), β is the strain rate parameter associated with the power law, and ξ_{95} is the accumulated shear strains required to obtain 95% reduction of the shear strength. For small deformations, the dynamic undrained shear modulus also depends on the shear strain rate and can be estimated as:

$$G_u(\delta\gamma) = G_{u,ref}\left(\frac{\delta\gamma}{\delta\gamma_{ref}}\right)^{\beta} \quad (2)$$

Table 1 summarizes the various model parameters considered in the study. The reference undrained shear strength ($s_{u,ref}$) of clay is set to be 6.5 kPa based on the results from Triaxial experiments. The value of reference shear strength ($\delta\gamma_{ref}$) is calculated to be 0.56 s^{-1} based on cone penetration test (CPT) [3]. The simulation uses all the other material parameters same as those used for the numerical replication of the fall cone test and model FF-CPT simulation in [11,12].

Table 1: Material parameters for numerical simulation

$s_{u,ref}$ (kPa)	$\delta\gamma_{ref}$ (s^{-1})	β	$G_{u,ref}$ (kPa)	v_u	S_t	ξ_{95} (s^{-1})	ρ (kN/m^3)	μ
6.5	0.56	0.08	$167 s_{u,ref}$	0.495	10	10	15	0.65

3 Numerical results

Figure 2 illustrates that the variation of FFP acceleration with depth obtained from numerical simulation closely matches that obtained from FF-CPTs. The final penetration depth obtained from the numerical simulation is 1.78 meters, which aligns well with the experimental range of 1.8 to 1.95 meters. In Figure 3a, the final displacement contour of the FFP is depicted. Figure 3b shows the variation of shear strain rate in the soil at time t = 0.12 seconds from the start of penetration. The shear strain rate is predominant at the tip of the FFP and in the soil layer surrounding it. As indicated in Equations (1) and (2), the undrained shear strength in these regions is expected to increase with an increase in shear strain rate. Figure 3c displays the variation of normalized undrained shear strength ($s_u/s_{u,ref}$) in the domain at time t = 0.12 seconds from the start of penetration. It demonstrates that the undrained shear strength of the soil surrounding the FFP (approximately 0.01 meters) reduces drastically due to a very high accumulation of shear strain in that region. Destructuration has a more predominant influence in this region. Beyond that region, the effect of strain rate on the strength of the soil is predominant.

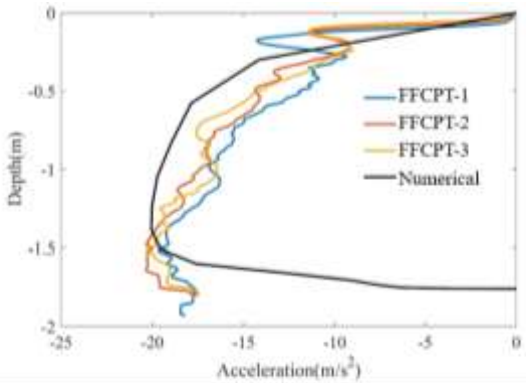
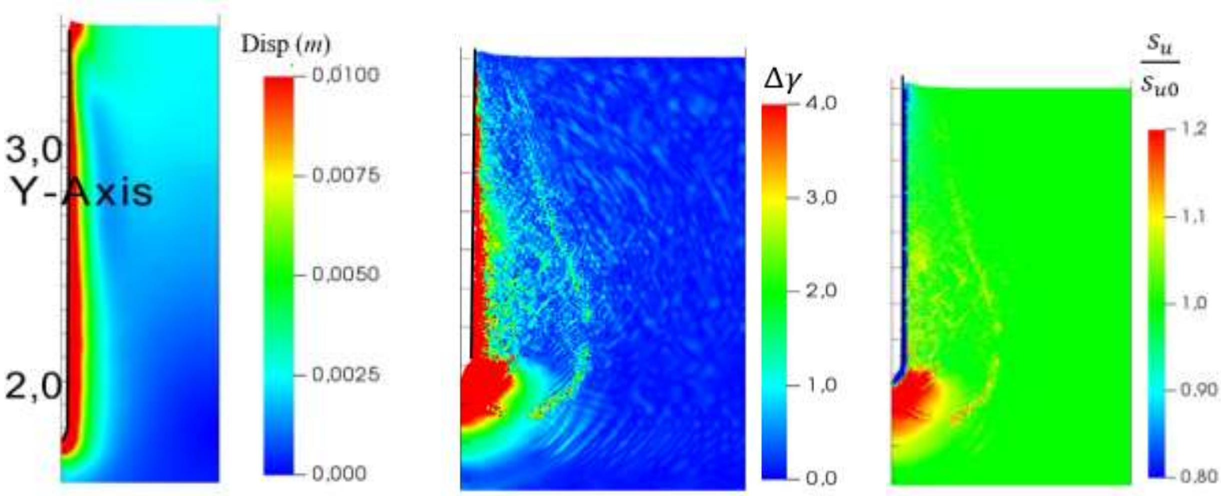


Figure 2: Variation of cone acceleration with depth.



(a) t=1 sec. (b) t=0.12 sec. (c) t =0.12sec

Figure 3: (a) The displacement contour at the end of FF-CPT, (b) Contour of shear strain rate at t= 0.12 sec., and (c) Contour of normalized undrained shear strength at t = 0.12sec.

4 Conclusions

This paper presents a comprehensive numerical simulation of a free fall cone penetrometer test conducted at an offshore site using the Generalized Interpolation Material Point Method (GIMP). The undrained shear strength of the clay obtained from laboratory triaxial tests is utilized for the numerical simulation. An extended Tresca material model is employed to account for the effects of strain rate and strain softening caused by the destructuration of clay during the dynamic cone penetration process. The simulation utilizes the same material parameters as those employed in previous numerical replications of fall cone tests and laboratory-scale FF-CPTs [9,10]. The experimental results are accurately reproduced by the numerical simulation, demonstrating that the numerical framework employed in this study can effectively capture the dynamic penetration mechanism associated with soft and sensitive clays.

Acknowledgments

This research is part of the Geomeasure project, funded by the Academy of Finland (grant number 347602).

References

[1] Stark N, Hay AE, Trowse G. Cost-effective geotechnical and sedimentological early site assessment for ocean renewable energies. 2014 Oceans - St John's, OCEANS.

[2] Chow SH, Airey DW. Soil strength characterisation using free-falling penetrometers. *Geotechnique* 2013;63:1131–1143.

[3] Chow SH, O'Loughlin CD, White DJ, Randolph MF. An extended interpretation of the free-fall piezocone test in clay. *Geotechnique* 2017;67:1090–1103.

[4] Bezuijen A, Den Hamer DA, Vincke L, Geirnaert K. Free fall cone tests in kaolin clay. *Physical Modelling in Geotechnics* 2018;1:285–91.

[5] Chow SH, Asce AM, Airey DW. Free-Falling Penetrometers: A Laboratory Investigation in Clay. *Journal of Geotechnical and Geoenvironmental Engineering* 2014;140:201–214.

[6] Moavenian MH, Nazem M, Carter JP, Randolph MF. Numerical analysis of penetrometers free-falling into soil with shear strength increasing linearly with depth. *Computers and Geotechnics* 2016;72:57–66.

[7] Zambrano-Cruzatty L, Yerro A. Numerical simulation of a free fall penetrometer deployment using the material point method. *Soils and Foundations* 2020;60:668–682.

[8] Bardenhagen SG, Guilkey JE, Roessig KM, Brackbill JU, Witzel WM, Foster JC. An Improved Contact Algorithm for the Material Point Method and Application to Stress Propagation in Granular Material. CMES 2001;2:509–22.

[9] Tran QA, Sołowski W. Generalized Interpolation Material Point Method modelling of large deformation problems including strain-rate effects – Application to penetration and progressive failure problems. *Computers and Geotechnics* 2019;106:249–65.

[10] Einav I, Randolph M. Effect of strain rate on mobilised strength and thickness of curved shear bands. *Geotechnique* 2006;56:501–504.

[11] Mohapatra D, Li Z, Saresma M, Virtasalo J, Solowski W. Replication of fall cone test on marine clay with a Generalized Interpolation Material Point Method simulation. In: Zdravkovic L KSTDTA, editor. *10th European Conference on Numerical Methods in Geotechnical Engineering*, 2023, p. 1–7.

[12] Mohapatra D, Saresma M, Virtalaso J, Solowski W. Numerical Simulation of a Laboratory-Scale Free Fall Cone Penetrometer Test in Marine Clay with the Material Point Method. *VIII International Conference on Particle-Based Methods*, CIMNE; 2023.