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Application of Coupled Eulerian-Lagrangian Method to Large Deformation Analyses of Offshore Foundations and Suction Anchors

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Finite element analysis (FEA) using the Coupled Eulerian-Lagrangian (CEL) method has gained greater acceptance and increasing application to offshore geotechnical problems involving large deformation. This paper focuses on applying the CEL method to deep penetration analyses of the spudcan foundation and suction anchors. Some well-controlled centrifuge tests available in the literature are selected for the back analyses. A real case of spudcan-subsea template interaction during installation of the spudcan foundation at the Brynhild field is analyzed. Some semi-empirical methods recommended in industry guidelines and the small strain finite element (FE) method with the Press-Replace (PR) technique are also utilized for predicting the spudcan penetration capacity. From a comparison of all the results, it is concluded that combining the CEL method with the modified Mohr-Coulomb constitutive model provides a robust and suitable numerical tool for not only estimating the foundation-bearing capacity but also predicting complex failure mechanisms.

INTRODUCTION

During installation of offshore foundations and anchors, the soil might undergo large deformation. The effects of installation, such as penetration resistance, squeezing failure, punch-through failure, and changes in contact stresses and strengths, should be accounted for in the design and planning. Such effects have been typically assessed through the use of semi-empirical methods and engineering judgment skills obtained from field and model testing. Over the past two decades, large deformation finite element (LDFE) analysis has been extensively applied to evaluate the installation effects of the deep penetration of offshore foundations and anchors. Using the LDFE analysis does not require any *a priori* assumption of a failure mechanism, and thus the LDFE analysis can reflect the natural development of the failure zone and provide reasonably good prediction of the bearing behaviour. Wang and Carter (2002), Hossain and Randolph (2010b), and Yu et al. (2012) employed the Remeshing and Interpolating Technique with Small Strain (RITSS) developed by Hu and Randolph (1998) to simulate the penetration process of spudcan foundations in stratified soils. This RITSS method falls into the category of Arbitrary Lagrangian-Eulerian (ALE) methods. Qiu and Grabe (2012), Tho et al. (2012), Khoa (2013), Hu et al. (2014), and Zheng et al. (2014) recently applied the Coupled Eulerian-Lagrangian (CEL) method to the finite element program, Abaqus, to simulate the large installation of spudcan foundations.

Andresen and Khoa (2013) applied both the ALE and CEL methods available in Abaqus to model the deep penetration process and installation effects of offshore anchors and spudcan foundations. From a comparison of the two approaches, it was concluded that in the Abaqus program, the ALE method is more flexible since it can be applied to planar, axisymmetric, and three-dimensional boundary value problems, whereas the CEL method can be applied only to three-dimensional boundary value problems. Moreover, the ALE method is also available for both Abaqus/Explicit and Abaqus/Standard, which largely expands its application fields to steady-state transport analysis, coupled pore fluid flow and stress analysis, and coupled temperature-displacement analysis. However, the main limitation of the ALE method in Abaqus is that it does not support the boundaries between different materials that are considered to be nonadaptive mesh (or Lagrangian) boundaries. In other words, this method cannot handle a deep penetration problem in layered soils where large deformations can take place at the material boundary regions.

The main objective of this paper is to apply the CEL method to analyze the effects of the deep penetration of spudcan foundations and suction anchors. 3D CEL FE models are constructed through the use of the Abaqus/Explicit program. In particular, the classical Mohr-Coulomb model in Abaqus/Explicit is modified through the introduction of a hyperbolic evolution of the internal variables, i.e., the friction angle, dilatancy angle, and cohesion, as a function of the Von Mises equivalent plastic strain that was proposed by Barnichon (1998). This simple modification reported by Khoa (2013) allows the material to harden and/or soften isotropically. Thus, the modified Mohr-Coulomb model can be used to model the soil strength degradation as the plastic shear strain is increasing during the penetration process. According to the authors' knowledge, many other researchers have modelled the material-softening behaviour in their CEL FE analyses by using different strain-softening functions proposed by Einav and Randolph (2005) and Potts et al. (1990) or by using even more advanced constitutive models such as the visco-hypoplasticity model (Qiu and Grabe, 2012) and the modified Cam-Clay model (Yi et al., 2014). The advantage of the modified Mohr-Coulomb model presented in this paper is that it is relatively simple to implement and use. This can make the model useful for both engineering practice and research purposes.

In the first section of this paper, some well-controlled centrifuge tests of spudcan foundations penetrating various soil profiles, including a single clay layer, two soil layers, and multi-layered soils, are back-analyzed through the use of the semi-empirical methods currently recommended in industry guidelines (SNAME, 2008; InSafeJIP, 2011; ISO, 2012) and the CEL method. The

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