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Free Fall Penetration of Ball Penetrometers in Clay

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This paper presents numerical modelling and analysis of free fall (under gravity) penetration of a ball penetrometer in uniform and normally consolidated clay. A coupled Eulerian Lagrangian technique is employed in a finite element framework to simulate the penetration process. Final depth of penetration (d_p) values are obtained for a range of relevant parameters (i.e., impact velocity, penetrometer mass and diameter, and seabed shear strength). Analysis-based equations are proposed to estimate d_p. The proposed methodology can be used to select values of test parameters for achieving a desired penetration depth. Numerical predictions are in excellent agreement with published field and laboratory test data.

INTRODUCTION

Strength characterization of seabed soil is essential for the safe design, installation, and operation of an offshore energy infrastructure. However, extraction of undisturbed soil samples from a deep water seabed is extremely difficult because of the presence of very soft soil deposits. Hence, in situ soil strength characterization has long been preferred by the offshore geotechnical engineering community. The use of conventional in situ soil strength characterization techniques in harsh offshore conditions is not simple, either. Moreover, such exploration techniques require specialized driving machinery that makes the testing program time consuming and expensive. Owing to the simplicity of use and the time and cost efficiency of the test procedure, free fall penetrometers (FFPs) may offer a pragmatic solution to problems associated with conventional in situ offshore site exploration techniques.

FFPs are first lowered into the water from a moving or stationary vessel and then released (with zero initial velocity) from a certain height above the seabed to fall under gravity. FFP accumulates velocity, because of gravitational acceleration, during its "free" fall through water and hits the seabed with a certain impact velocity. Apart from hydrodynamic factors, the impact velocity depends on the height (above the seabed) of the fall, the mass, and the shape of the FFP tool. After the impact, the FFP tool penetrates through the seabed and starts decelerating as a result of the resistance offered by the soil. The penetration process continues until the tool comes to a complete halt (i.e., when FFP velocity becomes equal to 0). FFPs are generally used for soil characterization of a few meters below the mudline. Such seabed characterization within a shallow depth below the mudline aids in the design of several subsea infrastructure facilities. Example of such infrastructure includes oil well heads and pipeline end terminals that are embedded to very shallow depths and pipelines that run through several kilometers on the seabed. The major potential application of FFPs is thus in characterization, down to shallow depths, of a very large area of a deep water seabed. FFPs of different shapes and sizes have been developed and tested in the field. Some of the commonly adopted geometries are (a) ball without shaft, such as, for example, an instrumented free fall sphere, or IFFS (Morton et al., 2016); (b) a cylindrical shaft with conical tip, such as, for example, a free fall cone penetrometer,or FFCPT (Stegmann et al., 2006); Nimrod (Stark et al., 2017); and (c) a thin cylindrical shaft with plate tip, such as, for example, a seabed terminal impact naval gauge, or STING (Mulhearn, 2003). Attached sensors (e.g., accelerometer, load cell) continuously record data during FFP penetration. Recorded data are used to derive a soil shear strength profile using the force equilibrium method (Jeanjean et al., 2012; Morton et al., 2016; Chow et al., 2017) or energy balance method (Mana et al., 2018). The final depth of FFP penetration can also be derived from recorded accelerometer data.

Several laboratory (Chow and Airey, 2013, 2014), field (Morton et al., 2016), and numerical (Aubeny and Shi, 2006; Abelev et al., 2009; Nazem et al., 2012; Moavenian et al., 2016; Mana et al., 2018) studies that investigated FFP penetration are present in literature. However, previous studies primarily focused on the development of methods that can be used to determine soil shear strength from data recorded during FFP penetration. Note that the penetration process of FFP is not controlled externally; consequently, the maximum possible depth of penetration is unknown before the test. It is expected that the maximum penetration depth would depend on the amount of total energy possessed by the FFP tool at the time of hitting the seabed surface, the geometry and mass of the FFP tool, and the shear strength of the seabed. The objective of this research is to develop closed-form analytical expressions to predict maximum penetration depth d_p for a free fall ball penetrometer (similar to IFFS) in clay. Such expressions are beneficial for predicting the depth (i.e., depth of penetration d_p) that can be explored for a given set of test parameters (e.g., FFP mass, diameter, and impact velocity) and for different in situ shear strength conditions. FFP tests are often accompanied by other conventional in situ shear strength characterization tests in nearby locations. Soil shear strength estimated from such tests can be used as input for the methodology described in this paper. In the absence of any exact knowledge of in situ soil shear strength profile at a site, a range of preliminary values of undrained shear strength s_u can be assumed based on information on local geology and seabed conditions so that expected variations of exploration depth with test parameters can be computed. The proposed methodology is also useful in deciding the appropriate values of test parameters (i.e., penetrometer mass, diameter, and impact velocity) to attain a desired depth of exploration (i.e., final penetration depth).

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