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Research Paper

Numerical analysis of penetrometers free-falling into soil with shear strength increasing linearly with depth

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ABSTRACT

Dynamic penetrometers have been used for offshore oil and gas industry applications such as pipeline feasibility studies and anchoring systems, and military applications including naval mine countermeasures and terminal ballistic studies. The main challenge of using dynamic penetrometers is the interpretation of their test results in order to deduce the mechanical properties of the penetrated soil via empirical or theoretical relations. Recently, a robust numerical method based on the Arbitrary Lagrangian–Eulerian (ALE) technique has been developed for analysing dynamic penetration problems and used to investigate a smooth penetrometer free falling into a uniform layer of clayey soil. Numerical as well as experimental results indicate that the penetration characteristics, including the impact energy, total time, and total depth of penetration, depend on the mechanical properties of the soil including its stiffness and strength parameters as well as the geometry of the penetrometer and its initial impact energy. In this study, the ALE method is employed to study the effect of shear strength increasing with depth (a common condition of seabed deposits) on the penetration characteristics of a free falling penetrometer. Conducting more than two thousand numerical simulations has shown that there is an approximate quadratic relation between the final embedment depth of a FFP penetrating into a non-uniform clay soil and the combined kinetic energy on contact with the soil and subsequent loss in potential energy of the penetrometer.

1. Introduction

In engineering practice, laboratory and in situ tests are used to measure the geotechnical properties of the ground, which are essential in the design and construction of a wide range of physical infrastructure, such as bridges, dams, roads, landfills, pipelines, and offshore platforms. Penetrometers are probably the most popular devices for in situ testing. For instance, the static cone penetration test (CPT) is now a standard in situ testing procedure to explore the geotechnical properties of soil layers as well as their stratigraphy. This test is often conducted for major infrastructure projects in order to gain vital information on soil properties, but it cannot be undertaken easily in sites where the soil is relatively inaccessible such as many deep seabed deposits. On such sites free falling penetrometers (FFP) have been employed to provide information on the mechanical properties of the soil [26].

FFP tests can provide useful data, such as the total depth and time of penetration and the deceleration characteristics of the falling penetrometer. Potentially, these data can then be used to deduce strength parameters for the soil in situ [5,22]. An expendable dynamic penetrometer was used by Beard [3] to measure seafloor penetrability and its undrained shear strength in deep sea regions. A range of dynamic penetrometers were tested by Denness et al. [10] in an attempt to improve data quality and to explore ways of reducing the cost of testing. They recognised that penetrometers can be used not only as an investigation tool, but also as a potential delivery vehicle for radio-active waste canisters. Stoll et al. [31] and Aubeny and Shi [2] used free falling penetrometers to determine the undrained shear strength of seafloor sediments. Stark et al. [29] used the Nimrod free-falling penetrometer to investigate the shear strength of quartz sand as well as carbonate sand in the North Sea. Further investigations on the soil properties obtained from dynamic penetration were conducted by Steiner et al. [30]. Three different types of seabed penetrometer were described and compared by Stoll et al. [32].

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Recent advances in computational methods have facilitated numerical analysis of the cone penetration test. The finite element method is perhaps the most popular approach for analysing penetration problems in geomechanics [1,5,13,15,27,34,36]. The analysis of dynamic penetration is probably one of the most challenging problems in computational geomechanics. From the point of view of geometrical non-linearity, the penetration of objects into layers of soil potentially involves severe mesh distortion and entanglement of elements caused by the large deformations. This usually motivates the application of adaptive finite-element techniques, such as the Arbitrary Lagrangian–Eulerian (ALE) method, which can successfully overcome the mesh distortion issue. Moreover, the analyst must also consider the relative incompressibility of soil during the short period of penetration, the likelihood of material inhomogeneity, nonlinear stress–strain relations, and the rate-dependency of the material being penetrated. High speed impact with the soil and inertia effects during penetration may also be important. The analyst must also be aware of the possible reflection of stress waves in a finite-element domain usually surrounded by fictitious rigid boundaries. More importantly, the boundary conditions of the problem do not remain constant during the analysis, since the interface between the penetrometer and the soil changes continuously during penetration.

Among the important parameters mentioned above, this study considers specifically the effect of inhomogeneity of the soil (in respect of strength varying continuously with depth, rather than interbedded layers of differing properties) on the penetration characteristic of a free-falling penetrometer. It is well known that the shear strength of many soils, including those located on the seabed, usually increases with depth [28], and this variation is often assumed to be linear, at least as a first engineering approximation. Raymond [25] considered this effect on the bearing capacity of large footings as well as embankments. Davis and Booker [8] studied the effect of a linear increase of shear strength with depth on the bearing capacity of clay soils under strip footings by means of the theory of plasticity. They concluded that the surface cohesion (undrained shear strength) and rate of increase of cohesion with depth play important and independent roles in determining the bearing capacity. Merifield et al. [18] studied the pullout capacity of anchors in an undrained layer of clay in which the shear strength increases with depth. Lu et al. [14] conducted a numerical investigation of the effect of non-uniformity of marine clays on the capacity factors of the T-bar, ball and plate penetrometers. It is notable that in all the studies mentioned above it was assumed that penetration of the soil occurred under static conditions, neglecting the effect of inertia forces.

A preliminary study by Nazem and Carter [21] indicated that, in the case of a FFP, the non-uniformity of soil affects its dynamic response. However, until now this effect has not been studied extensively and reported in the literature. This paper describes a comprehensive parametric study conducted to further understand the effect of increasing shear strength with depth on the penetration characteristics of a FFP. This study was achieved by employing a validated numerical approach based on the ALE method previously developed by Nazem et al. [23,22]. Based on the numerical results obtained in the study, relations are established between the total depth of penetration and controlling parameters such as the initial impact energy of the penetrometer and the mechanical properties of the soil including its stiffness, strength (including the gradient with depth) and rate-dependency.

2. Problem definition and assumptions

A free falling penetrometer with a conical tip is allowed to penetrate into a layer of soil in which the undrained shear strength increases linearly with depth. The initial impact velocity, the mass, and the diameter of the penetrometer are assumed to be v_0, m and d, respectively, as shown in Fig. 1. The total depth and the total time of penetration are attained when the FFP comes to rest, and are denoted by p and t_p, respectively. In order to study the effect of the shear strength of soil on the penetration resistance, the initial stress field due to soil weight is ignored, i.e., it is assumed that the initial total stress components are all zero. Due to the relatively rapid penetration, the soil response is considered to be undrained and the soil is modelled as a Tresca material with an associated plastic flow rule. Poisson's ratio of the soil is assumed to be 0.49 to approximate elastic incompressibility. It is assumed that the undrained shear strength of the soil increases with the strain rate according to [12]:

$$s_u = s_{u,ref}\left[1 + \lambda \log\left(Max\left(\frac{\dot{\gamma}}{\dot{\gamma}_{ref}}, 1\right)\right)\right] \quad (1)$$

where s_u is the undrained shear strength of soil, $s_{u,ref}$ denotes the reference undrained shear strength measured at a reference strain rate of $\dot{\gamma}_{ref}$, λ is the rate of increase of strength per log cycle of time, and $\dot{\gamma}$ represents the shear strain rate. The value of $\dot{\gamma}_{ref}$ is assumed to be 1%/h (2.78 s^{-1}) [11]. Because of the need to restrict the range of strain rate for which this relationship holds, $s_{u,ref}$ is also a minimum shear strength, ignoring lower strengths that might be measured at even lower strain rates. The effect of ignoring such low strengths is considered negligible for the problem investigated. Eq. (1) is just one of a number of possible equations that could be used to quantify the effect of strain rate on strength (e.g., as discussed by [4]). It has been selected because of its widespread use for clays and its demonstrated applicability to soft, normally or lightly overconsolidated marine soils [16].

As depicted in Fig. 1, it is also assumed that the shear strength of the clay increases linearly with depth according to

$$s_{u,ref(z)} = s_{u,ref(0)} + k_s z \quad (2)$$

where $s_{u,ref(z)}$ and $s_{u,ref(0)}$ are respectively the undrained shear strength at depth z and the ground surface, and k_s represents the

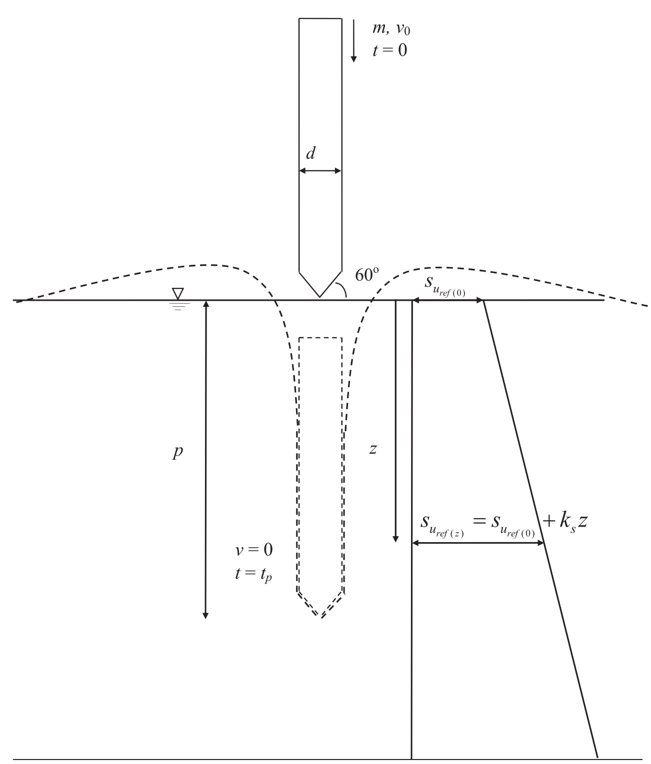

Fig. 1. FTP problem definition.