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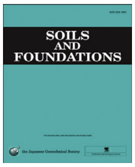

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Layered effects on soil displacement around a penetrometer

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Abstract

The interpretation of cone penetration test (CPT) data is important for the in-situ characterisation of soils. Interpretation of CPT data remains a predominately empirical process due to the lack of a rigorous model that can relate soil properties to penetrometer readings. Interpretation is especially difficult in layered soils, where penetrometer response can be affected by several horizons of soil with different properties. This paper aims to provide some insight into the mechanisms of soil displacement that occur as a penetrometer is pushed into layered soils. Data is presented from centrifuge modelling of probe penetration in layered soils in an axisymmetric container where soil deformation patterns around the probe can be measured. Results obtained from uniform soil tests are also presented to illustrate the effects of soil density and stress level (i.e. centrifuge acceleration). A large influence zone is found to relate to the higher penetration resistance obtained in a denser soil. Differing soil displacement patterns at low and high stresses are related to the tendency of the soil to dilate, with the well-known consequence of a non-linear increase of penetration resistance with stress level. Layered soil tests show a clear difference of soil deformation patterns compared to uniform tests, especially for vertical displacements. The peak value of vertical displacement of the soil occurs at dense-over-loose interfaces, while a local minimum occurs at loose-over-dense interfaces. Parameters are proposed to quantitatively evaluate the layered effects on soil deformations and a deformation mechanism is described for penetration in layered soils based on the transition of displacement profiles.

Keywords: Cone penetration test; Soil displacement; Layered effect

1. Introduction

Cone penetration tests (CPT) are frequently used in geotechnical engineering for in-situ evaluations of soil properties and profiles. CPT data is also valuable for use within pile design methods and for the evaluation of soil liquefaction potential. The response of a CPT is very complex; it relates not only to the mechanical properties of the soil in which the probe tip is penetrating, but also the properties and proximity of nearby horizons of soil. As such, rigorous analysis of CPT data is very difficult and interpretation generally relies on empirical relationships for soil identification and classification (Sadrekarimi, 2016).

The CPT probe generates a complex deformation field as it penetrates into the soil. For plane-strain conditions, a comprehensive illustration of soil patterns around a flat-bottomed penetrometer was provided by White (2002) and White and Bolton (2004). The tests were conducted at 1g (g = gravity) within a pressure chamber, and the results include streamlines of soil movement and stress profiles at the base of the penetrometer. The evolution of soil element deformation was illustrated and the reduction

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of stresses above the pile tip was related to cavity contraction caused by the densification of soil around the shaft. Mo (2014) reported results from axisymmetric elevated-g tests using a geotechnical centrifuge in which a half-cylindrical probe with a conical tip was pushed along a Perspex wall into both uniform and layered soil profiles. A resistance ratio was proposed in order to evaluate the transition curve of penetration resistance as the probe moved from one soil layer to another. A fully three-dimensional investigation was achieved by Paniagua et al. (2013) by using digital image correlation on X-ray micro tomography data. The authors were able to evaluate deformations around a fully-cylindrical penetrometer pushed into pressurised samples of silt. Failure patterns were described from the evolution of volumetric and shear strains.

Natural soil deposits often consist of layers with varying thickness and mechanical properties. Gui and Bolton (1998) reported that the CPT profile in layered soils deviates from a uniform soil profile when the probe reaches a certain distance from the soil layer interface and that some distance is required to develop a new tip resistance once the probe has penetrated into the second soil layer. Thus the transition zone around the soil layer interface can be separated into two parts: (1) the transition zone above the interface in which the probe begins to sense the underlining soil layer, and (2) the transition zone below the interface which extends to the depth where the probe is no longer influenced by the upper soil layer. Transition zones around soil layer interfaces have been shown to depend on the properties and thickness of soil layers (Meyerhof and Sastry, 1978a, 1978b; Youd and Idriss, 2001; Mo et al., 2015). Analytical methods (e.g. Vreugdenhil et al., 1994; Mo et al., 2017) and numerical approaches (e.g. Ahmadi and Robertson, 2005; Xu, 2007; Walker and Yu, 2010) have also been performed to investigate penetration problems in layered soils. Despite these valuable contributions, there is still a limited amount of data available on penetration induced soil deformations within layered soils.

In this paper, data obtained from geotechnical centrifuge modelling of cone penetration tests in layered soils are included, with a particular emphasis on the illustration of soil deformations around the probe. The experimental equipment is the same as that presented in Mo et al. (2015); the penetrometer consisted of a half-cylindrical probe with a conical tip which was pushed into the soil at a Perspex wall in an axisymmetric container, thereby enabling the measurement of subsurface soil movements using digital image analysis. The paper first discusses the effect of soil density and stress level effect on deformation patterns. This is followed by a detailed illustration of the effect of soil layering on soil deformation patterns. The paper supplements the work presented in Mo et al. (2015, 2017) in several ways: (1) additional results are presented that relate to the effects of stress condition; (2) the method for interpreting layered effects on soil displacements is elaborated; (3) profiles of displacements after penetration are presented which indicate different mechanisms for a loose-over-dense compared to a dense-over-loose configuration of soil layers; and (4) transition parameters of both horizontal and vertical displacements are introduced to quantitatively evaluate the layered effects on soil displacements, which are also related to the transitions based on penetration resistance.

2. Centrifuge tests and soil deformation measurement

Centrifuge tests were conducted using Fraction E silica sand (mean grain size $d_{50} = 0.14$ mm) with layers of varying relative density in a 180° axisymmetric model. Tests were performed on the Nottingham Centre for Geomechanics (NCG) 2 m radius geotechnical centrifuge. The penetrometer had a diameter of $B = 12$ mm and was pushed into the sand at a speed of 1 mm/s. Soil models were prepared by the multiple-sieving air pluviation method (Mo et al., 2015) to either a relatively dense state with relative density (D_r) of approximately 90% or a relatively loose state with relative density of approximately 50%. Note that the relatively loose sand, referred to simply as loose in this paper, falls within the ‘medium dense’ range ($D_r = 35$–65%), and the relatively dense sand, referred to as dense, falls within the ‘very dense’ range ($D_r = 85$–100%), based on BS EN ISO 14688–2:2004. Tests were performed at both 50g (centrifuge acceleration) and 1g to evaluate the effects of stress level. Note that at prototype scale, the penetrometer represents a 0.6 m diameter pile, which is comparable to a typical full-scale driven pile. The comparison between 50g and 1g results aims to provide an indication of the effect of stress condition on the induced soil deformation mechanism. Details of the layered soil profiles are summarised in Table 1.

A half-cylindrical model container with a Perspex window was used to enable the observation of penetration-induced sub-surface soil deformations, as shown in Fig. 1(a). Digital cameras were used to obtain a series of images of the penetrometer and soil throughout the tests. Soil deformations caused by the penetrometer, schematically presented in Fig. 1(b), were measured using the Matlab-based image analysis methodology ‘geoPIV’ developed by White et al. (2003). Note that ‘X’ and ‘Y’ represent the horizontal and vertical positions of soil elements, and ‘Δx’ and ‘Δy’ indicate horizontal and vertical displacements, respectively. ‘H’, defined as $H = z - z_{interface}$, indicates the distance between the cone shoulder and the soil layer interface. The upper soil layer interface is taken as the location of $z_{interface}$ (Fig. 1b) to define H for multi-layered tests. Further details on test set-up and procedures can be found in Mo (2014).

3. Results and discussion

3.1. Effects of soil density

It has been demonstrated that the response of a penetrometer in granular soils is dominated by two factors:

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