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3D finite element simulation of a single-tip horizontal penetrometer–soil interaction. Part II: Soil bin verification of the model in a clay-loam soil

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ABSTRACT

Horizontal penetrometers have been recently examined as instruments for on-the-go mapping of soil strength/compaction. Since the horizontal penetrometer resistance (PR) provides a composite soil strength parameter, it needs to be characterized with respect to variations in soil physical properties as well as standardized with respect to the operational parameters of the device. In a recent study, a 3D finite element (FE) model was developed for a single-tip horizontal penetrometer–soil interaction (cf. Part I of this study; Naderi-Boldaji et al., 2013b) and the effect of some soil/operational parameters (mechanical properties of soil, model boundary effects, penetrometer tip extension, working depth and soil failure mode ahead of the tine) on PR was investigated. In the second part of this study, two soil bin tests were conducted to evaluate the PR predictability of the FE model. This is a crucial step for finite element modelling of soil compaction reflected by PR as affected by soil water content, bulk density and texture. The soil bin tests were carried out in a clay loam soil at two different water contents of 0.171 and 0.183 g g^{-1} and dry bulk densities of 1.64 and 1.59 Mg m^{-3}, respectively, to evaluate the model at two different levels of PR. The soil elastic parameters (i.e. Young's modulus of elasticity and Poisson's ratio) were estimated from oedometer (uniaxial compression) tests on confined and unconfined undisturbed samples taken within the working depth of the penetrometer whilst the plastic parameters (the parameters of the Drucker–Prager constitutive model) were determined by triaxial tests at three levels of confining stress. The results indicated the practical and efficient use of oedometer tests for estimating soil elastic parameters for numerical simulations. The FE model predicted the measured PR with a small error ($<12\%$) when modelling the soil as elastic-perfectly plastic material, whilst the prediction error was found to be significantly higher when soil hardening was included. This may suggest that the confinement of soil around the moving cone is different than in a confined compression test. It is concluded that the FE model presented here and the procedures used for estimation of the model input parameters reflected well the change in soil physical conditions of the two tests. Further evaluations are needed to generalize the model predictions across soil types and characterize PR with respect to soil physical properties.

1. Introduction

The finite element method (FEM) is a powerful numerical technique that can be used to analyze complicated engineering problems. It is particularly useful for problems with geometric and/or material nonlinearities, as well as situations where

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underlying differential equations describing physical or biological phenomena are nonlinear. Since most soil–machine interaction problems involve both material and geometric nonlinearities, FEM has been widely used to analyze soil/machine interaction problems (Upadhyaya et al., 2002; Mootaz et al., 2004; Hemmat et al., 2012; Bentaher et al., 2013). It should be noted that intrinsic to the use of FEM in the context of soil–machine interaction is the assumption that continuum mechanics applies to this case (Upadhyaya et al., 2002).

Soil–tool interactions are usually characterized by two phenomena: forces arising at the soil–tool interface (draught, side and vertical forces) and displacement of soil particles (soil disturbance) (Conte et al., 2011 cited in Chen et al., 2013). A complete investigation of the soil–tool interaction requires many experiments to be carried out in a controlled situation (e.g. a soil bin) in a range of variations in soil physical state (e.g. water content and bulk density) and operational conditions of the tool (e.g. geometry, travelling speed, working depth) (Mouazen et al., 1999). Analytical models, although helping in the understanding of basic relationships, do not consider all the details of a soil–tool interaction. Moreover, the initial assumptions in developing the analytical models may distance the problem from reality.

A verified FE model can be efficiently used to predict the forces on any tool moving through the soil and develop prediction models for the forces as a function of either soil mechanical properties (e.g. internal angle of friction, cohesion, modulus of elasticity) or a function of soil physical characteristics (e.g. water content, bulk density and texture) (Mouazen and Ramon, 2002). The FE model can be also employed for design and optimization of tools (Mouazen and Neményi, 1999). However, one of the main challenges in validation of a FE model is how to estimate the model input parameters and whether the estimated parameters using the corresponding methodology logically reflect the changes in soil physical state. This is especially important for estimation of soil elastic parameters as there are different laboratory procedures and tests to estimate them (e.g. uniaxial compression test, triaxial test). In fact, the values of the parameters are methodology-dependent but it is crucial to investigate whether the FE predictions reflect realistically the change in the soil physical state using the estimated input parameters.

The horizontal penetrometer is one of the most popular on-the-go soil strength sensors widely used for mapping soil compaction (Hemmat and Adamchuk, 2008). Its popularity is because it can be developed with discrete depth probes to measure the profile of soil strength when moving through the soil. It is well known that the horizontal penetrometer resistance (PR) is a composite soil parameter and basically a function of several soil physical properties (e.g. Naderi-Boldaji et al., 2012, 2013a). In addition, the operational parameters of the device (e.g. design and geometry, working depth and travelling speed) affect PR, and hence characterizing PR with respect to the affecting parameters is a fundamental step to employing the horizontal penetrometer (Naderi-Boldaji et al., 2013b).

In the first part of this study (Naderi-Boldaji et al., 2013b) a 3D finite element model was developed for a single-tip horizontal penetrometer–soil interaction. Evaluation of the model parameters (cf. Part 1) showed that the model output (i.e. PR) is most sensitive with respect to parameters of the linear Drucker–Prager model (e.g. internal angle of friction) and to the soil compressive yield stress. It was also indicated that the minimum allowable tip extension (i.e. the distance between cone base and the front face of the carrying tine) for the given horizontal penetrometer dimensions and soil specifications was 4 cm to minimize the interference of soil disturbance by the tine on the predicted PR. Moreover, it was concluded that PR reflects the strength of a 10–12 cm thick soil layer and that the zone of plastic strain was small (ca. 2 cm radius) around the moving tip.

This study aimed to validate the FE-predicted PR by soil bin tests of a horizontal penetrometer with emphasis on estimating the model input parameters from undisturbed soil samples taken within the working depth of the penetrometer in soil bin. A validated FE model of the horizontal penetrometer–soil interaction can be used to characterize PR with respect to soil mechanical properties as affected by soil type and soil conditions (e.g. texture, soil moisture). Such a model can also be employed to develop a prediction model for PR as a function of soil physical properties (Mouazen and Ramon, 2002). Furthermore, FE modelling has been suggested by Mouazen and Ramon (2002) as a calibration method of sensor fusion systems of soil compaction (e.g. Naderi-Boldaji et al., 2013a).

2. Materials and methods

2.1. Finite element simulation of the horizontal penetrometer-soil interaction

A symmetric 3D model was developed in ABAQUS/Explicit, and this has been described in Naderi-Boldaji et al. (2013b). The model consists of three ABAQUS parts: (1) deformable soil box, (2) rigid tine and (3) rigid cone, as shown in Fig. 1. Since the model was symmetric about the central plane, only one-half of the total region was considered and the predicted forces were then duplicated in magnitude in order to obtain the total forces. The single-tip horizontal penetrometer consisting of a (discrete) rigid body tine (half-thickness of 12.5 mm, 100 mm width and 700 mm depth) and a (discrete) rigid cone (30 mm diameter, 45° apex angle, 16 mm shaft diameter) was modelled. The frictional horizontal penetrometer–soil interaction was simulated with a general contact law and tangential behaviour. For general contact, ABAQUS/Explicit enforces contact constraints using a penalty contact method, which searches for node-into-face and edge-into-edge penetrations. The C3D8R element type was used for meshing the soil box whilst the rigid bodies were meshed with R3D4.

Boundary conditions applied were: (1) both side walls of the box (in y–z plane) were constrained in positive and negative x directions (roller), (2) the bottom face of the box (in x–z plane) was constrained in both y and z directions (to prevent movement of the

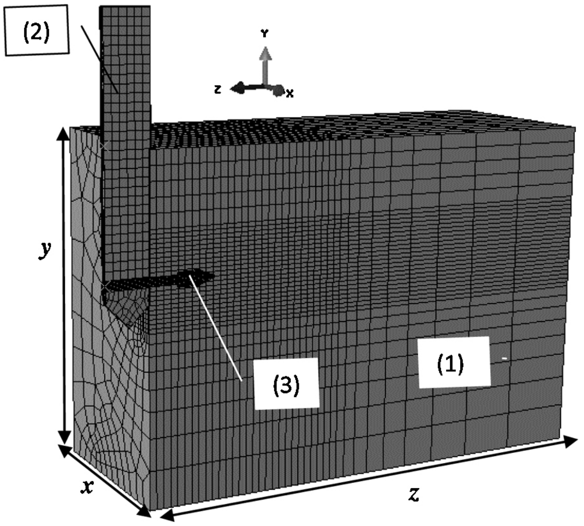

Fig. 1. 3D symmetric FE model developed for horizontal penetrometer–soil interaction; (1) soil box, (2) tine and (3) cone
After Naderi-Boldaji et al. (2013b).