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Determination of in-situ engineering properties of soil using an inverse solution technique and limited field tests

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ABSTRACT

The goal of this research is to develop a response surface based inverse solution technique to determine in-situ engineering properties of soil for use in mobility and traction prediction models from the force displacement data generated by a cone penetrometer device. The nonlinear elasto-plastic behavior of soil was characterized by a six-parameter constitutive model – two elastic parameters (i.e., bulk modulus, K and the Poisson's ratio, υ), three plastic parameters (i.e., angle of internal friction φ, cohesion c, and soil hardening parameter λ), and one soil physical condition parameter (i.e. initial void ratio, e^*). Soil failure was represented by the Drucker-Prager yield criterion and associated flow rule. LS-DYNA FEM software package was used to model the soil-cone interaction problem. FEM simulations were conducted for a set of soil properties properly selected within the defined parameter space. The analysis of FEM simulations indicated that the cone penetration force-displacement curves could be represented by two piecewise smooth functions – a parabola followed by a straight line. The coefficients of these two curves were used to create fourth order response surfaces using a stepwise multiple linear regression technique. The results showed both cohesion and soil hardening parameter could be predicted using this methodology.

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1. Introduction

Mobility and tractive performance are critical aspects in designing off-road vehicles (ORVs) that operate over a wide range of terrains and soil conditions. The high variability in terrains and soil conditions challenge the effective design of traction devices (i.e., tire or track) to attain the optimum tractive efficiency while minimizing excessive soil compaction (Garciano et al., 2012; Tiwari et al., 2010; Upadhyaya et al., 1987; Wong, 1997). One approach to design traction devices or predict their performance under various operating conditions is to develop a suitable model for soil-tractive device interaction process. As a prerequisite for successful modeling of traction devices or predict their performance under various operating conditions, engineering properties of soil must be identified and determined accurately. Reliable prediction of soil properties is very challenging due to the non-homogeneous, nonlinear, and elasto-plastic nature of soil. In order to develop a sound mathematical model, a reliable constitutive relationship describing the stress-strain and yield behavior of soil is critical (Rubinstein et al., 1994; Thangavadivelu et al., 1994).

Techniques of inverse analysis have been developed and applied for determining engineering properties of materials. The conventional approach in inverse analysis is to minimize the difference between the actual system responses and model predicted responses to estimate soil properties. Numerical simulations with Drucker-Prager yield criterion have been used to establish soil-cone interaction model by several researchers in the past (Tekeste et al., 2007; Li et al., 2014; Zhang et al., 2018). This approach relies on conducting numerous numerical simulations (finite element or discrete element) to determine the system parameters during the optimization process, making the inverse solution approach computationally expensive to use. To reduce the reliance on the time-consuming numerical simulations during the optimization process, we have proposed an alternate technique based on the response surface methodology (Rubinstein and Upadhyaya, 2001; Rubinstein et al., 1994; Sime and Upadhyaya, 2004). In this approach, only a few numerical simulations are performed at preselected material property values that are chosen for the response surface design.

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Sime and Upadhyaya (2004) found that soil deformation under quasi-static loading conditions was primarily governed by the plastic behavior that can be described by three engineering parameters (angle of internal friction (φ), cohesion (c), and soil hardening parameter (λ)). However, when the response surface based inverse solution technique was used to determine these three properties, often non-unique solutions were obtained. Therefore, the overall goal of this study was to further develop the inverse solution technique for determination of in-situ engineering properties of soil using force-displacement data generated from a standard cone penetrometer (ASABE standards, 2013) on the basis of response surface design. Specific objectives of this study were to:

(1) Develop a finite element model to simulate cone penetration process over a wide range of soil properties,
(2) Select the soil properties that have a significant effect on the cone penetration force,
(3) Develop and validate response surface model that can adequately represent cone penetration process in the soil,
(4) Predict the relevant soil properties using the response surface model.

2. Model development

2.1. Soil constitutive model

Soil was considered to be a continuum of nonlinear elasto-plastic material with strain hardening behavior and is assumed to undergo a process of continuous yielding until it reaches an ultimate strength defined by the Drucker-Prager yield criterion (Desai and Siriwardane, 1984) during the loading process.

Hardening, an increase in yield stress under normal load, usually occurs in soil materials and can be represented using an appropriate soil hardening parameter λ. Normal consolidation behavior is usually presented in the hydrostatic pressure versus total logarithmic volumetric strain plane (Li and Upadhyaya, 2014). This relationship was used as it is consistent with the form of the normal consolidation line used in the commercial FEM software, LS-DYNA (Hallquist, 2007), which was used in this study. The other elastic parameters such as the shear modulus (G) and Young's modulus (E) can be calculated knowing elastic bulk modulus (K) and Poisson's ratio (ν). The initial void ratio (e^*) representing the initial condition of the soil is an important parameter to describe the state of the soil. In summary, we considered a total of six parameters, (i) bulk modulus K, (ii) Poisson's ratio ν, (iii) initial void ratio e^*, (iv) angle of internal friction φ, (v) cohesion c, and (vi) soil hardening parameter λ in this study.

2.2. Finite element analysis

Simulation of the cone penetration process was formulated as a two-dimensional axisymmetric problem. Fig. 1 shows the detailed geometric information of the model implemented in LS-DYNA (Hallquist, 2007). We set the left boundary as the axis of symmetry, assigned the topsoil surface as free surface boundary and constrained the bottom and the right outer edge boundary. As boundary effects could exist in cone penetration tests (Bolton et al., 1999), the effects of boundary size were studied. Our simulations showed that when the dimensions of soil mass was set as 450 mm deep by 100 mm wide, the cone penetration process had little influence on the stress distribution at the bottom and outer boundary of the soil mass. The contact surface was restricted to the conical surface of the penetrometer.

In the critical soil-cone interaction region (50 mm by 225 mm region as shown in Fig. 1), uniform and dense quadrilateral elements of 1 mm in size were used. In the rest of the soil mass, coarser mesh sizes were used such that the mesh size gradually increased from fine meshed region to the boundary (Li and Upadhyaya, 2014). The yield behavior in the soil mass was represented by the Drucker-Prager yield criterion and hardening law as defined by the normal consolidation curve. At the interface between the cone and soil, normal stress acting on the cone-soil interface was calculated based on a penalty function method by defining the soil as a slave body and the cone as a master body (Hallquist, 2006). At the interface, sliding was allowed to occur when the nodes on the soil (slave body) were in contact with the cone (master body) and when the tangential stress exceeded the yield stress. In other words, the nodes on the slave surface of the soil responded elastically first (stick with the cone) and then yielded plastically (sliding along the cone when the contact tangential stress along the soil-cone interface exceeded the critical shear stress). The critical shear stress at the penetrometer-soil interface was assumed to be in a form similar to the Mohr-Coulomb yield function (Li and Upadhyaya, 2014). To avoid large soil deformation around the contact area that can affect the prediction accuracy and computational efficiency, the Lagrangian element method with an erosion criterion based on maximum shear strain of 0.75 was selected to model the soil-cone interaction problem. Note that the adhesion was ignored because its value is relatively small, and the critical shear stress was assumed to be governed mainly by Coulomb friction. Hettiaratchi (1997) suggested a fixed roughness ratio of 0.70 (i.e., $\psi/\varphi = 0.7$) for polished metal surface interacting with soil. Thus, in the present study, the value of soil-metal friction angle (ψ) was determined based on the corresponding angle of internal friction (φ) between soil particles.

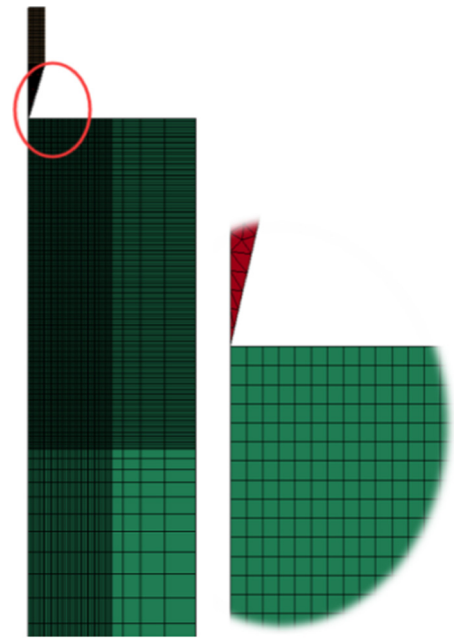

Fig. 1. Representative two-dimensional axisymmetric model developed for cone penetration simulation (left) and enlarged mesh size in the critical area (right). On the left is cone penetration simulation and the critical soil-cone interaction region is 50 mm by 225 mm. On the right is the enlarged mesh size in the critical area shown in left part.

3. Design of numerical experiments

In this study, six soil parameters were considered initially. As mentioned previously, these parameters were the bulk modulus (K), Poisson's ratio (ν), initial void ratio (e^*), angle of internal friction (φ), cohesion (c), and soil hardening parameter (λ)). During

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