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Harnessing Numerical Tools to Study the Limitations of CPTs for Characterizing Complex Soil Stratigraphies for Liquefaction Assessment

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ABSTRACT

This paper describes the use of the Material Point Method (MPM) to simulate cone penetrometer testing (CPT) in complex soil profiles. CPT-based liquefaction evaluation procedures have been shown to be inaccurate in highly interlayered soil stratigraphies. One contributing factor to this inaccuracy is that CPT measurements at discrete depths reflect the properties of all soils that fall within a zone of influence around the cone tip, not just the properties of the soil at a particular depth. Consequently, the CPT loses resolution in soil profiles with many thin, interbedded soil layers (multiple thin-layer effects) and provides inaccurate input data to liquefaction analyses. While several procedures have been proposed to correct for multiple thin-layer effects, they tend to decrease in efficacy as the thickness of soil layers decreases. Results from the MPM analyses detailed in this paper highlight limitations of (1) the CPT in characterizing complex soil stratigraphies and (2) procedures proposed to correct for multiple thin-layer effects in CPT data.

Introduction

Cone penetrometer tests (CPTs) are a preferred method for in-situ soil characterization for liquefaction assessment because they collect data at very small depth increments (typically 1 to 2 cm), providing nearly continuous profiles of the subsurface. Standard-of-practice CPT-based liquefaction severity procedures (i.e., stress-based liquefaction triggering models coupled with manifestation models) have been shown to work well for relatively uniform, sandy soil profiles (e.g., [1]). However, for complex soil profiles comprising many interbedded layers of potentially liquefiable and non-liquefiable soils, the procedures tend to overestimate the severity of liquefaction manifestation (e.g., [2]; [3]).

One contributor to this overestimation is multiple thin-layer effects, in which data collected in layered profiles by the CPT is "smoothed" [4]. This occurs because CPT data (i.e., tip resistance, q_c, and sleeve friction, f_s) recorded at discrete depths are reflective of the soil that falls within a zone of influence around the tip of the cone, not just of the soil at a given depth. The zone of influence varies in size depending on the diameter of the cone (d_{cone}) and properties of the soils in the profile and can extend between 10 to 30 times d_{cone} below the cone tip [5], for example. Several researchers have proposed procedures to correct for multiple thin-layer effects in CPT data (e.g., [6]-[8]). However,

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existing procedures have decreasing efficacy as the thickness of interbedded layers decreases, particularly when the layer thickness is less than 2 to $3d_{cone}$ [7].

To develop, validate, and assess the efficacy of multiple-thin-layer correction procedures, it is necessary to have sets of "true" data (i.e., data that would be recorded by the CPT absent of multiple thin-layer effects) and "measured" data (i.e., data actually recorded by the CPT) for the same layered soil profiles. The availability of this data is relatively scarce, as it can only come from calibration chamber tests or numerical analyses; note that field CPT data only provide "measured" data. To this end, this paper shows how advanced numerical tools such as the Material Point Method (MPM) can be used to numerically simulate CPTs in layered soil profiles to better understand the limitations of (1) the CPT in characterizing complex soil profiles for liquefaction assessment and (2) the procedures proposed to correct for multiple thin-layer effects in CPT data.

Background

Previous numerical studies of CPTs in layered soils performed using the Finite Element or Finite Difference Methods (FEM or FDM, e.g. [5]; [9]-[11]) have shown that the size of the zone of influence around the cone tip is strongly influenced by the type of soil, the stiffness ratio between soil layers, and the effective horizontal stress. However, none of these studies examined what happens when more than two or three soil layers are present in sequence in a profile. Furthermore, FEM and FDM require adaptive re-meshing techniques to accommodate the large soil deformations associated with cone penetration. We propose MPM as an alternative procedure for this application.

MPM, originally proposed by Sulsky et al. [12], is a continuum-based numerical framework that adopts features both of point-based and mesh-based numerical methods. In MPM, the continuum is discretized into a set of material points (MPs) that carry material data and move through a background computational mesh. The momentum balance equations are solved at the locations of the mesh nodes, but the constitutive equations and the mass balance equations are solved at the locations of the MPs. No permanent data are stored at the nodes. Data are mapped from the MPs to the nodes and vice versa at each time step using shape functions. This avoids problems with mesh distortion and makes MPM particularly suited for problems with large soil deformations, like cone penetration.

Methods

The analyses discussed herein were performed using a modified version of the open-source Anura3D MPM software [13]. This MPM formulation incorporates several advancements to the standard MPM formulation, all of which are detailed in Yost et al. [14]. The MPM CPT model used for this study was first calibrated and validated with a set of CPT calibration chamber test data collected by de Lange [15]. de Lange [15] performed CPTs in layered sand-clay profiles as well as "reference" single-layer sand profiles with similar confining pressure and sand relative density (D_R) as the layered models. The former tests provided "measured" q_c in the layered profiles, or q^m, which was impacted by multiple thin-layer effects. The latter tests provided "true" q_c for the sand layers in the layered profiles, or q^t_{sand}, in the sense that the q_c recorded by the CPT in the reference sand profile would be the q_c recorded by the CPT in the sand layers of the layered profile absent of multiple thin-layer effects.

A 2D-axisymmetric MPM model was created, mimicking the geometry from de Lange [15]. The model geometry and discretization are shown in Figure 1. The left boundary is the axis of symmetry and represents the center of the cone. The cone has an apex angle of 60° and d_{cone} = 25.3 mm. The left and right boundaries of the model were fixed in the horizontal direction, and the top and bottom boundaries were fixed in the horizontal and vertical directions. The entire vertical height of the calibration chamber (i.e., ~1 m of soil, or ~$40d_{cone}$) was included in the MPM model, but to minimize the computational time, the radial dimension was reduced to $10d_{cone}$ from the axis of symmetry.

Triangular mesh elements were assigned. A refined mesh was used in the region immediately adjacent to the cone, and more MPs were assigned per element in this area as well. A moving mesh technique [16] was used, allowing the portion of mesh above the cone tip to advance downward at the same velocity as the cone while the portion of mesh below the cone tip compresses. In this way, the cone-soil interface remains well defined throughout the calculation, which is essential for the accuracy of the contact formulation and the model's overall performance [17]. The forces

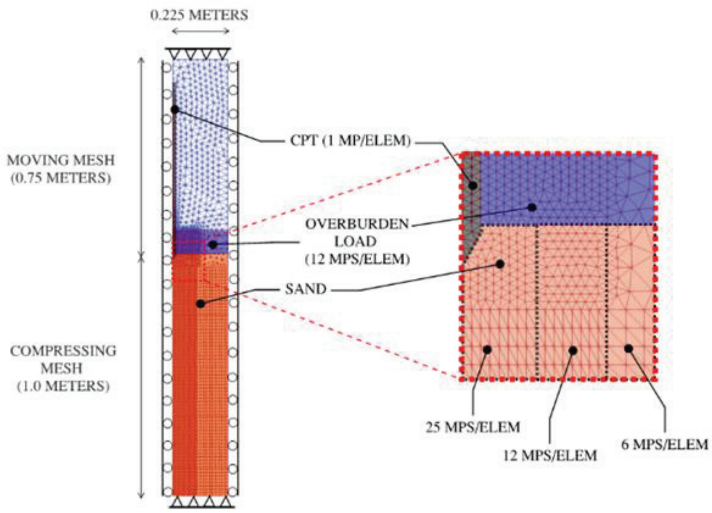

Figure 1. MPM model geometry and discretization [14].

imparted on the conical face of the penetrometer by the soil were computed and converted to stress using the known cone tip area. This stress is equivalent to the q_c measured by the CPTs in the lab.

All soils in the MPM model were assumed to be saturated. Clay layers were assumed to behave undrained and were modeled using a total stress method and the Tresca failure criterion. Sand layers were assumed to behave drained and were modeled using a strain-softening Mohr-Coulomb constitutive model [18]. During the calibration and validation phase, the calibration chamber tests [15] were replicated using the MPM model, and laboratory and numerical results were compared. Appropriate material parameters for each simulation were identified based on available laboratory data (see Yost et al. [14] for details). The MPM model was shown to be capable of adequately replicating q_c in both reference sand and layered sand-clay soil profiles, despite the use of the simplified drainage conditions and basic constitutive models described previously. Complete details regarding the calibration and validation of the model can be found in Yost et al. [14].

Results and Discussion

After the MPM model was calibrated and validated, it was used to study multiple thin-layer effects for a variety of soil profile geometries. A set of simulations was performed using four soil profiles with 0.28-meter-thick zones of alternating sand and clay layers. The four profiles had different layer thickness to cone diameter ratios (H/d_{cone}): 1.6, 1.2, 0.8, and 0.4. The resulting q_c profiles were considered to be q^m for the layered profiles. In order to compare q^m determined for each profile to the true q_c that would be expected in the sand and clay layers (q^t_{sand} and q^t_{clay}), two additional CPT simulations were performed considering a single layer of sand and clay. All simulations considered a vertical overburden pressure of 50 kPa, K_0 = 0.5 conditions, and sand D_R = 54% (if sand were present in the profile). The results are shown in Figure 2.

Several observations can be made from this exercise. First, q^m in the thin sand layers is significantly smaller than the q^t_{sand}. q^m in the thin clay layers is slightly larger than q^t_{clay}. In other words, q_c in thin, dense layers is significantly underestimated, and slightly overestimated in thin, soft layers. As H/d_{cone} decreases, both of these effects are magnified. Furthermore, boundaries between sand and clay layers are increasingly blurred as H/d_{cone} decreases, to the point where identification of the presence and location of thin layers from q^m data alone is nearly impossible for $H/d_{cone} < 0.8$. Finally, as H/d_{cone} decreases, q^m in the layered zone tends to converge to a single value that is much closer to q^t_{clay} than to $q^t_{sand.}$

The results of these simulations highlight the difficulties in attempting to correct CPT data for multiple thin-layer effects. Many correction procedures (e.g., [6]) require the detection of layer interfaces in q^m data. But if the variation in q^m is so small that no distinction between individual layers can be made (i.e., the CPT is not detecting the layer interface at all), the correction procedures will not work. For example, the entire layered zone in Figure 2 with H/d_{cone}

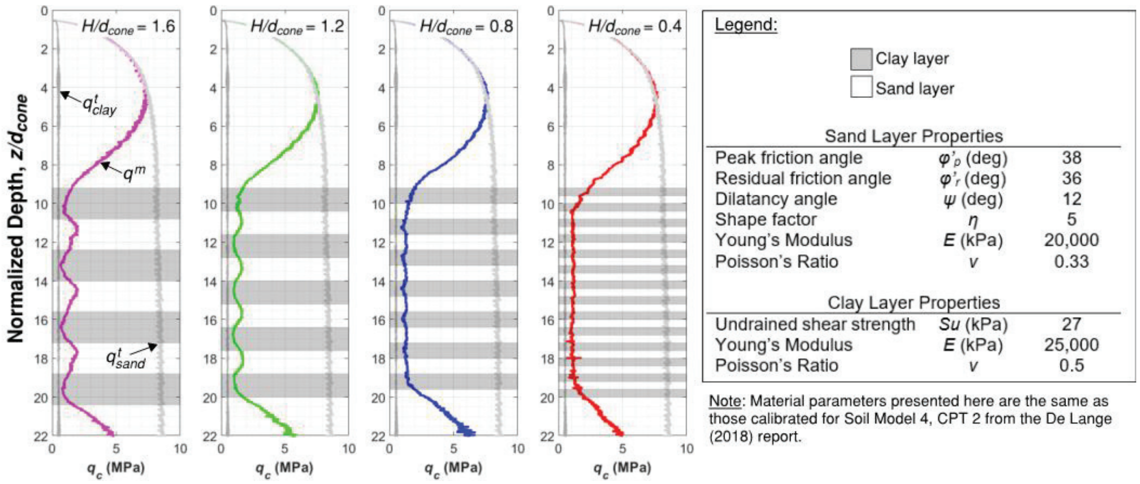

Figure 2. Multiple thin-layer effects on tip resistance for profiles with varying layer thickness (modified from [14]).

= 0.4 may be mistaken for a 0.28-meter-thick uniform layer of soil. The results also highlight the non-uniqueness of q^m; namely, soil stratigraphies with different layer thicknesses and stiffnesses can have essentially the same q^m. Consequently, procedures that attempt to extract q^t from q^m must be used with caution and should include techniques to reduce the uncertainty of the solution, e.g., by incorporating physically realistic constraints on what the q^t profile can look like. The efficacy of correction procedures may be increased by using large sets of numerically-developed q^m and q^t as training data, as suggested by Yost et al. [14].

Finally, most research has focused on addressing multiple thin-layer effects on q_c. However, the impact of multiple thin-layer effects on f_s is even more complicated. The relatively long length of the friction sleeve results in it being in contact with multiple thin layers at once. Also, there is a downdrag effect in which the advancing cone drags soil from overlying layers down into underlying layers, creating a zone of material immediately adjacent to the cone that is not representative of a given layer (shown physically by de Lange [15] and numerically by Yost et al. [14]). Both q_c and f_s are required for most CPT-based liquefaction evaluation procedures, and their accuracy impacts the accuracy of the predicted liquefaction response. Future work should address multiple thin-layer effects on f_s, in addition to q_c, in order to obtain accurate liquefaction evaluations.

Conclusions

In this paper, MPM is used to numerically simulate CPTs in highly stratified soil profiles. The results highlight the limitations of the CPT in characterizing complex soil stratigraphies for liquefaction assessment, as well as the limitations of the correction procedures developed to overcome the limitations of the CPT. The CPT loses its ability to detect the presence of very thin soil layers as the ratio of layer thickness to cone diameter gets smaller, a phenomenon referred to as multiple thin-layer effects. The efficacy of multiple-thin-layer correction procedures that rely on the cone's ability to detect layer interfaces is poor for profiles that have very thin soil layers relative to the diameter of the cone. Furthermore, correction procedures must be used with caution due to the non-uniqueness of measured q_c and should include physically realistic constraints to reduce uncertainty in their solutions. Finally, the impact of multiple thin-layer effects on CPT sleeve friction should also be considered in future work because both q_c and f_s are required for CPT-based liquefaction evaluation.

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