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Closure to "Axisymmetric Simulations of Cone Penetration in Saturated Clay" by D.M. Moug, R.W. Boulanger, J.T. DeJong, and R.A. Jaeger

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The published paper presented an axisymmetric cone penetration model and simulations of cone penetration in saturated clay with the Mohr-Coulomb (MC), modified Cam clay (MCC), and MIT-S1 constitutive models calibrated to Boston Blue Clay (BBC) behavior as documented in experimental data. The two primary objectives of the paper were:

- to validate the penetration model and implementation of the MIT-S1 constitutive model for FLAC in order to move forward with studies on intermediate soils, and
- to investigate the effects of s_u anisotropy on cone penetration in saturated clay.

Two discussions were submitted in response to the paper: one by Konkol and Balachowski, and another by Koutsoftas. The main discussion points were: the role of strain rate effects (SRE) on cone-penetration resistance (q_t), aspects of constitutive model calibrations, and comparison of the simulated q_t with measured q_t. These are addressed in the three sections below.

Strain Rate Effects

Konkol and Balachowski submitted questions on the role of SRE during cone penetration in saturated clay, and how SRE were accounted for in the study. The cone penetration model presented in the paper does not include SRE in the model simulations or in the constitutive model calibration. The Authors agree that not accounting for SRE in the interpretation of the penetration simulations is a limitation of the study, and we appreciate the opportunity to elaborate on how SRE are expected to affect the derived N_{kt} values.

Only one of the reported direct penetration models in Table 1 of the paper explicitly accounted for SRE in their investigations. The numerical study by Liyanapathirana (2009) used an elastic perfectly plastic constitutive model and incorporated SRE on s_u. Liyanapathirana (2009) found an approximately 35% increase in N_{kt} from analyses with no SRE to analyses with a 10% increase in s_u over one log cycle increase in shear strain rate ($\dot{\varepsilon}$). The Authors expect that including SRE in the study would yield similar increases in derived N_{kt} values. However, the effect for in-situ conditions would likely vary with OCR since SRE decrease with increasing OCR (Sheahan et al. 1996, Pestana et al. 2002).

The loading condition, and therefore $\dot{\varepsilon}$ distribution, around the penetrating cone is complex. Although the $\dot{\varepsilon}$ immediately adjacent to the penetrating cone tip may be close to 200,000% per hour as reported by Chen and Mayne (1994), the $\dot{\varepsilon}$ decreases rapidly with distance from the cone. The distribution of $\dot{\varepsilon}$ for the published MIT-S1 simulation in OCR = 2.2 Boston Blue clay (BBC) is shown in the below Figure 1 with $\dot{\varepsilon}$ plotted radially from the middle of the cone tip and vertically down from the cone tip. $\dot{\varepsilon}$ is close to 200,000% per hour immediately adjacent to the cone tip, and it quickly declines from the cone tip until it is less than 5% per hour at about 8 to 10 cone diameters away from the tip. Since simulated and measured q_t are influenced by a large zone around the penetrating cone, the influence of SRE on q_t depends on the

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distribution of $\dot{\varepsilon}$ and not just the high strain rate adjacent to the tip. Liyanapathirana's (2009) finding of a 35% increase in N_{kt} due to SRE reflects the cumulative effects of SRE throughout the zone of influence around the cone tip.

The N_{kt} values presented in the paper should be adjusted for the effects of SRE, which may be reasonably approximated based on Liyanapathirana (2009). If SRE results in a 35% increase in N_{kt}, where N_{kt} is referenced to s_u values at standard laboratory strain rates, then the adjusted $N_{kt,iso}$ values may be approximated as 13.1 and 12.8 for MC and MCC, respectively. The adjusted N_{kt} values for the anisotropic soil conditions would be $N_{kt,C} = 9.0, N_{kt,E} = 12.8, N_{kt,D} = 13.5$. Thus, the simulated q_t values of 750 for MC, 735 for MCC, and 536 kPa for MIT-S1 at 9.6 m bgs would be expected increase to about 947 kPa, 932 kPa, and 662 kPa, respectively if the constitutive model formulations included SRE.

The publication notes that N_{kt} should be referenced to a specific s_u loading condition (e.g., CK_0UC, CK_0UE, CK_0UDSS). In light of this discussion, N_{kt} could also include an index for the reference $\dot{\varepsilon}$ at which s_u is determined. For example, for CK_0UDSS loading, the suggested indexing would be:

$$N_{kt,DSS,\dot{\varepsilon}_{ref}} = \frac{q_t - \sigma_{vo}}{s_{u,DSS,\dot{\varepsilon}_{ref}}}$$

Omission of the $\dot{\varepsilon}_{ref}$ index would imply s_u corresponds to a standard laboratory $\dot{\varepsilon}$.

Constitutive model calibrations

The two submitted discussions raised questions about the constitutive model calibrations, specifically how the calibration of isotropic soil models (MC and MCC), and calibration of the MIT-S1 constitutive model were performed. These topics are addressed below.

Calibration of isotropic soil models

The Authors agree with Konkol and Balachowski that calibrating the MC and MCC models to the average s_u from CK_0UC, CK_0UE, and CK_0UDSS loading conditions (i.e. $s_{u,ave}$) is a valid approach that could have been selected for this study. If the MC and MCC models were calibrated for $s_{u,ave}$ rather than to the s_u for CK_0UC, then: (1) the resulting simulated q_t values would be smaller and perhaps closer to the MIT-S1 simulated q_t values, but (2) the $N_{kt,iso}$ values of 9.5 and 9.7 computed using the MC and MCC models would remain about the same because the simulated q_t values would reduce approximately proportionately to the reduction in the s_u value used for calibration. For this discussion, the cone penetration analyses at 9.6 m depth was repeated with the MC model calibrated to an $s_{u,ave}$ of 43 kPa which resulted in the simulated q_t decreasing to 617 kPa from 750 kPa and the $N_{kt,iso}$ actually increasing to 10.3 from 9.7; note that the shear modulus remained the same in both analyses, such that this slight increase in $N_{kt,iso}$ is consistent with a corresponding increase in the G/s_u. Thus, the $N_{kt,iso}$ values would still be slightly greater than the $N_{kt,ave}$ value of 8.7 obtained with MIT-S1.

The key advantage of using the MIT-S1 model for this study is that it provided insights into how q_t is affected by s_u anisotropy and it reinforces the observation that N_{kt} depends on the s_u loading condition to which it is referenced. The derived N_{kt} values require further modification for SRE, as noted in response to the discusser's first comment.

For geotechnical engineering practice, N_{kt} values are best calibrated on a site-specific basis, preferably using advanced laboratory tests on high-quality field samples, as was discussed by Koutsoftas. In this regard, the differences between the derived $N_{kt,iso}$ and $N_{kt,ave}$ values for the study site are small relative to the effects that site-specific calibration can have. With or without site-specific calibration of N_{kt} values, it is important to explicitly document the s_u loading condition to which the N_{kt} value is referenced/correlated.

Calibration of MIT-S1 soil model

The utility and calibration of complex constitutive models in geotechnical engineering have long been subjects of debate and discussion, with viewpoints often reflecting differences in technical backgrounds and whether the focus is on practical application or scientific inquiry. The discussion by Koutsoftas reflects a number of commonly raised issues, for which the authors provide a brief summary of their perspectives. The authors appreciate the opportunity to discuss these issues in the context of the study.

It is important to separate the tasks of soil/site characterization and constitutive model calibration. In characterizing a specific soil, it is the engineer's responsibility to determine the key engineering properties of concern and subsequently estimate them using the most appropriate tools and procedures. For example, characterizing a soft clay deposit may include estimating how s_u varies with consolidation stress, stress history, loading path, and strain rate, regardless of whether these estimates are based on correlations or direct measurements. In calibrating a constitutive model, the focus should then be on ensuring the constitutive model reproduces the key engineering properties (or behaviors) that were estimated in the soil characterization task. Essentially, the focus is not on directly measuring or isolating the individual constitutive parameters (i.e., the model inputs), which Koutsoftas noted is difficult due to spatial variability and sample disturbance effects, but rather on ensuring the selected input parameters produce the desired stress-strain behaviors (i.e., the model responses). In this manner, calibration of a constitutive model can leverage the body of empirical correlations routinely used in soil/site characterization practices, such that calibrations can be developed using a wide range of available site characterization data. A complex constitutive model can usually capture a soil's complex stress-strain behaviors more accurately than simple constitutive models, such that a good constitutive model calibrated with limited data can still offer advantages relative to a simple constitutive model.

The Authors recommend developing the MIT-S1 input parameters for a given soil and loading conditions using a combination of (i) site-specific laboratory testing, (ii) published relationships for soil behavior, and (iii) typical parameter values for similar soil types. Calibration of the MIT-S1 constitutive model for clayey soils requires selection of 13 of 16 model parameters (three parameters do not apply for clayey soils and are equal to zero). Several of the model parameters define specific behaviors of the model (i.e., the small-strain stiffness, critical state friction angle, virgin compression behavior) and are independent of the other parameters. However, some parameters have interrelated influences on the model behavior, such as the bounding/yield surface shape parameters (i.e. p_{ϕ}, m, ϕ_{mr}) which can influence the s_u predicted by the model, hardening behavior, and the critical state conditions. When calibrating to a single shearing test mode (e.g., CK_0UC), multiple parameter combinations may give the same peak s_u for that shearing mode. However, these different parameter combinations will lead to different s_u ratios for other shearing modes (e.g., CK_0UDSS, CK_0UE). As such, the Authors rely on single element simulations under multiple loading conditions, including one-dimensional compression, direct simple shear, triaxial compression, and triaxial extension loading conditions to demonstrate that the calibrated soil behavior reasonably agrees with observed soil behavior (i.e. with lab data) and with typical soil behavior relationships. Additional discussion of MIT-S1 calibration is provided in Moug et al. (2019) and Price (2017).

Koutsoftas raised questions of how s_u ratios from normally-consolidated to over-consolidated conditions are incorporated in the model calibration. The normally-consolidated s_u ratio predicted by the MIT-S1 model is not a direct input parameter, but a result of the model's formulation and a combination of input parameters. Over-consolidated behavior is predicted using a bounding surface plasticity approach, which incorporates an additional model parameter h, which specifically controls the elastoplastic modulus and accumulation of plastic strain in loading for over-consolidated states. As a result, the s_u ratios predicted for over-consolidated materials is a function of the same equations and parameters for normally-consolidated behavior, but also h. Pestana et al. (2002) compared MIT-S1 predictions of s_u ratios of BBC to available laboratory data and found the model was able to reasonably predict the effect of OCR on s_u ratios for CK_0UC, CK_0UE, CIUC, CK_0UDSS, plane strain compression, and plane strain extension tests with OCRs ≤ 8.

Koutsoftas also noted virgin compression behavior and unloading behavior are stress-dependent and that model input parameters and model formulation should reflect this dependence. The model parameters

ρ_c and D were specifically addressed in the paper discussion. The model parameter ρ_c is the slope of the virgin compression curve in double logarithmic effective stress – void ratio space. Available data has shown that for clays, the parameter ρ_c is not stress-dependent over the range of interest for most geotechnical engineering practice (Pestana & Whittle 1999). The model parameter D is a model parameter that affects the unloading behavior at high OCRs and is used internally in the model to define the swelling slope (ρ_r). The Authors agree that ρ_r should be stress-dependent and we confirm the model does include a stress-dependence (Pestana et al. 1999; Jaeger 2012).

Simulated q_t vs. measured q_t

The Authors agree with Koutsoftas that the simulated q_t values from the three constitutive models agree reasonably with the measured q_t profiles. The Authors do not have enough information to speculate on which constitutive model calibration more closely captures cone penetration in BBC at the Newbury site. However, the study does demonstrate that including s_u anisotropy in cone penetration simulations affects simulated q_t due to the complex loading condition around the penetrating cone. Given that s_u anisotropy is established behavior for saturated clays, and for Boston Blue Clay in particular, it is reasonable to expect that analyses or interpretation of cone penetration in saturated clay should account for s_u anisotropy either directly or indirectly.

Conclusion

The Authors are grateful to the Discussers for their feedback and engagement with the paper. Future research efforts with the axisymmetric cone penetration model and MIT-S1 constitutive model will focus on cone penetration in intermediate soils. The ability to capture the full loading condition around the penetrating cone with the direct penetration model, and complex soil behavior with the MIT-S1 model will be advantageous to these studies. Future calibration of MIT-S1, interpretation of simulated results, and reporting of the results will benefit from the discussions provided in response to the paper.

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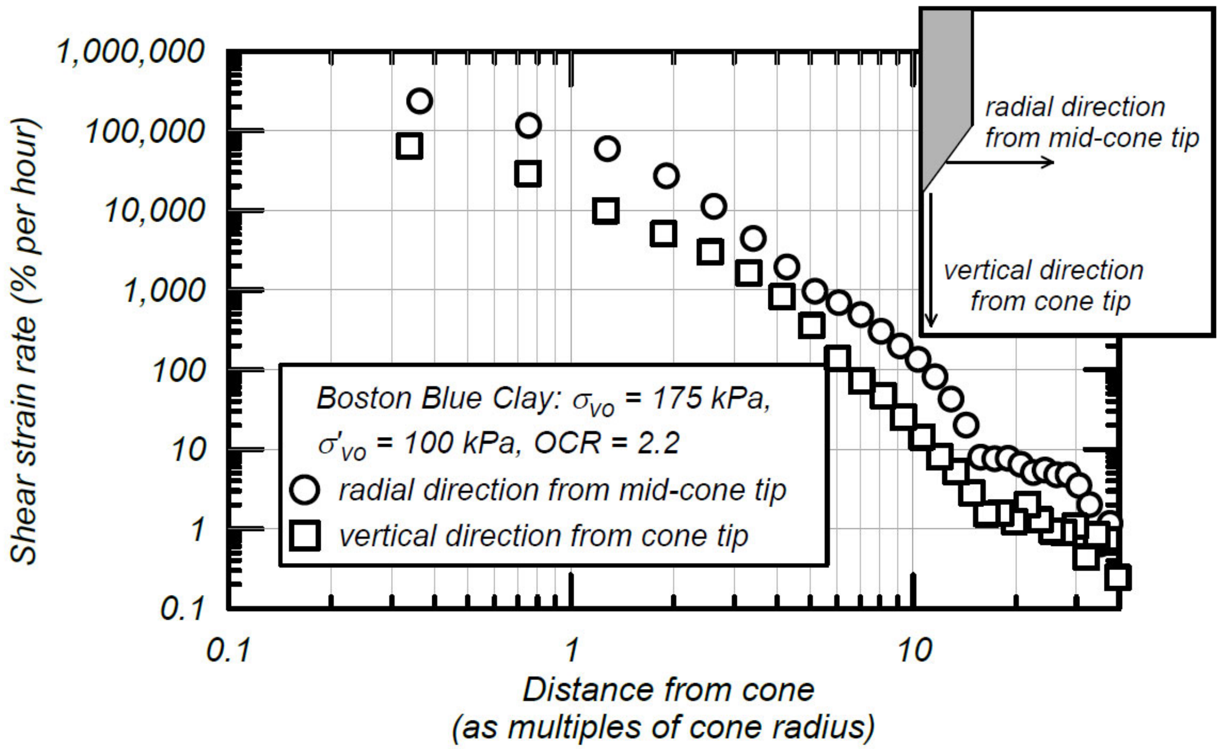

Fig 1: Simulated $\dot{\varepsilon}$ during steady-state penetration with MIT-S1 calibrated for BBC

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