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Discussion of "Characterization of Model Uncertainty for Cantilever Deflections in Undrained Clay" by D. M. Zhang, K. K. Phoon, H. W. Huang and Q. F. Hu

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Introduction

The authors have presented an interesting and welcome study of cantilever wall displacements due to the excavation of soil, first relating simplified Mobilized Strength Design (MSD) calculations (Osman and Bolton 2004, 2006) to more complex Finite Element Analyses (FEA) of a range of excavation geometries and wall stiffnesses, and then linking MSD principles to the probabilistic assessment of soil and model parameters. The calibration of MSD against FEA is welcome because it extends the earlier work of Osman and Bolton (2004), and does so in a rigorous fashion. Putting these calibrated MSD estimates into the framework of reliability, by allowing for uncertainty in the estimates of system parameters, is also welcome because it enables probabilistic decision-makers to focus on more realistic definitions of the failures they are seeking to avoid. The transition from notional concepts of ultimate failure, based on the statistics of peak strength, towards the statistical assessment of ground movements and their possible consequences, also requires an understanding of additional parametric uncertainties (e.g. Phoon and Kulhawy 1999). We agree with the authors that, to be practical, such assessments need to be made on the basis of simplified

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behavioural models and the simplest possible constitutive relations. We have some further comments that draw upon recently published work of the discussers.

Soil Stiffness Degradation

While the apparent accuracy of the finite element back-calculations of cantilever wall displacements in Figure 10 is excellent, they must be dependent on the HSSmall parameters, namely the shear modulus at very small strains (G_0), the elastic modulus as very small strains (E_0), the shear strain required to reduce G/G_0 to 0.7 ($\gamma_{0.7}$) and the asymptotic value of the deviatoric stress (q_a) introduced in equation 8. However, the authors' database of field case studies in Appendix II only lists an unload-reload modulus (E_{ur}), but does not precisely specify the strain magnitude at which it was determined. Could the authors offer further information?

The accuracy of their recalibrated displacement predictions compared with centrifuge test results, as shown by the authors in Figure 13, is also remarkable. However, this excellence of fit must surely also be regarded as fortuitous considering the apparently subjective definition chosen for the unload-reload modulus (E_{ur}), the assumption of a constant ratio E/s_u, the undeclared and uncertain relationship between E_{ur} and the parameters G_0 and q_a set out in equation 8, and the universal assumption of the quoted value of $\gamma_{0.7}$.

While these potential drawbacks inevitably introduce uncertainties and errors into the prediction of real wall displacements made using the authors' approach to the HSSmall soil model, they need not be taken to detract from the authors' calibration of MSD against FEA (via regression function *f* in equations 7 and 10) which use the same soil model in each case.

The established consensus is that the shear stiffness G_0 at very small strains should be measured, and must be understood to vary in service with the square root of mean effective stress. The shear stress at small to moderate strains can then best be estimated on the assumption of a quasi-hyperbolic stress-strain curve, conventionally normalised using the strain γ_{ref} which is found to reduce G/G_0 to 0.5. Darendeli (2001), Zhang et al. (2005) and Vardanega and Bolton (2013, 2014) present databases that offer statistical correlations against routine characterisation information such as the Atterberg Limits (and in the case of Vardanega and Bolton 2013, 2014 an allowance for relevant rate effects), enabling a prior fit to be obtained against the published stiffness reduction data of fine grained materials even before project-specific data becomes available.

A new approach for fine-grained soils does not rely on the measurement of G_0 but instead bases the non-linear stress-strain relation on knowledge of the undrained shear strength (s_u) and the measurement of the strain ($\gamma_{M=2}$) required to mobilise half of it. Vardanega and Bolton (2011, 2012) have shown that a power curve of normalised shear stress τ/s_u versus normalised shear strain $\gamma/\gamma_{M=2}$ raised to the power b, enables adequate strain predictions to be made for τ/s_u between 0.2 and 0.8 for 19 natural clays with widely varying characteristics. Furthermore, Vardanega et al. (2012) show evidence of the variation of $\gamma_{M=2}$ and b with overconsolidation ratio for a particular reconstituted kaolin. Some prior evidence therefore exists on the expected ranges within which project-specific parameter values should fall. The final establishment of satisfactory design values for the curve-fitting parameters s_u, $\gamma_{M=2}$ and b requires only competent triaxial tests on cores tested with an accuracy on strain of at least 0.02%, or equivalent pressuremeter tests in the field. Engineers may then conduct their own deterministic calculations of displacement with parameters chosen from a range of depth profiles for each of s_u, $\gamma_{M=2}$ and b.

Dimensionless Groups for Deep Excavations

The authors make a good finding of the regression function f between simplified MSD estimates of wall crest displacement and FEA estimates, related to six dimensionless groups namely, normalised excavation depth (H_c/D), normalised excavation width ($B/2D$), relative wall stiffness ($\gamma D^4/EI$), earth pressure coefficient (K_0), strength ratio (s_u/σ'_v) and stiffness ratio (E_{ur}/S_u). Two other groups may be worth studying in a similar fashion, in relation to the bulging of a braced wall below the level of the lowest installed prop. This mode of deformation usually leads to the greatest displacements, which occur below dredge level, creating a corresponding settlement trough in the retained ground. Therefore, bulging is usually critical in structural serviceability checks both for the retaining wall itself and any structure that rests on the retained ground.

Lam and Bolton (2011) and Lam et al. (2014) demonstrated some success in predicting the peak bulging displacement (w_{max}) using an energy balance for a MSD deformation mechanism based on the assumption of a sinusoidal bulge of wavelength (λ). Bolton et al. (2014) have recently published a follow-up study of excavations in Shanghai, analysing and extending the database of Xu (2007), and making use of the power law soil model introduced above. In this study a new dimensionless group is introduced in equation 1 to improve upon the system stiffness definition of Clough et al. (1989) which involved the prop spacing interval. A modified system stiffness, η^* (not to be confused with the residual random part of the MSD calibration, also denoted η^* in the original paper) was defined:

$$\eta^* = \frac{EI}{\gamma_w \lambda^4} \qquad (1)$$

This has the logical advantage of relating the wall flexural stiffness (EI) to the unsupported length (λ) of the bulging portion of the wall.

The bulge amplitude w_{max} was then expressed as a normalised shear strain in the retained ground, using the definition of modified mobilisation parameter ψ^*(expressed in terms of the mobilisation factor, M and b in equation 2)

$$\psi^* = \frac{2w_{max}}{\lambda_{average}\gamma_{M=2}} = \left(\frac{2}{M}\right)^{1/b} \qquad (2)$$

It was shown that field monitoring data mapped well on plots of ψ^* versus η^* when the range of soil strength profiles and excavation depths was allowed for. It would be interesting to see if η^* and ψ^* are also significant in an assessment of the correction factor η via f using the database presented in the paper under discussion, where wavelength λ would be replaced by wall depth D in the cantilever phase.

Notation

The following symbols are used in this paper:

b = an exponent

B = excavation width

D = wall depth

E = elastic modulus

EI = wall flexural stiffness

E_0 = elastic modulus at very small strains

E_{ur} = unload-reload modulus

f = a regression function

G = shear modulus

G_0 = shear modulus at very small strains

H_c = excavation depth

K_0 = earth pressure coefficient

M = mobilization factor

q_a = asymptotic value of the deviatoric stress

s_u = undrained shear strength

w_{max} = maximum wall bulge

γ = shear strain (or unit weight of soil when calculating relative wall stiffness)

$\gamma_{0.7}$ = shear strain required to reduce G/G_0 to 0.7

$\gamma_{M=2}$ = shear strain to mobilize $0.5s_u$

γ_{ref} = shear strain required to reduce G/G_0 to 0.5

γ_w = unit weight of water

η^* = modified system stiffness

λ = wavelength

σ'_v = vertical effective stress

τ = mobilized shear stress

ψ^* = modified mobilisation parameter

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