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Worst case scale of fluctuation in basal heave analysis involving spatially variable clays

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ABSTRACT

This study explores the phenomenon of a worst case scale of fluctuation (SOF) in basal heave analysis for excavation in spatially variable clays. In the literature, the worst case SOF refers to the SOF where the discrepancy between the mean response from random realizations and the nominal response from a soil mass taking mean properties everywhere is the largest. Random finite element method (RFEM) is adopted to simulate the basal heave factor of safety (FS_{FEM}). It is evident that the mean value of FS_{FEM} can be 10–15 percent smaller than its nominal value at some worst case SOF. It is also shown that the slip circle method (SCM) based on an assumed prescribed slip curve cannot capture the phenomenon of a worst case SOF. However, the SCM can be modified to allow the weakest slip curve in a spatially variable soil mass to be located among a set of statistically independent potential slip curves. This "weakest path" model can reproduce the mean and coefficient of variation of FS_{FEM} approximately *without* costly simulation when it is appropriately calibrated. In particular, the phenomenon of a worst case SOF can be captured, both qualitatively and quantitatively.

1. Introduction

Basal heave stability of excavations in soft clays are commonly evaluated by limit equilibrium analyses, such as the stability models proposed by Terzaghi [41] and Bjerrum and Eide [3], and the slip circle model [32, 42] that is widely adopted in Japan and Taiwan. These models do not consider the spatial variability in natural soils. However, soils are spatially variable due to natural geologic formation processes. This spatial variability has profound impact on the behavior of a geotechnical system. In particular, Luo et al. [33] and Wu et al. [46] conducted analyses on the basal heave stability of excavations in soft clays by considering the spatial variability in the undrained shear strength (s_u) along the *prescribed* slip curve. Their observations are similar: the mean value of the factor of safety (FS) is the same as the nominal FS evaluated with s_u = its mean value (because FS is a linear function of the spatially averaged s_u), whereas the coefficient of variation of FS depends on the scale of fluctuation (SOF).

However, the impact of spatial variability on the performance of geotechnical systems is more complex than what has been envisaged in these earlier studies. A series of studies conducted by the authors [5,6,10] showed that the *mobilized* shear strength is not the spatial average along any *prescribed* curve but the spatial average along the critical slip curve. The main difference is that the critical slip curve is not a prescribed curve but an emergent curve that is produced by finite element analysis with a random field (spatially varying) realization as input field. In general, a critical slip curve depends on both the location and persistence of weak zones in a spatially varying medium as well as mechanics (equilibrium, compatibility, constitutive model, and boundary conditions). In some problems, the role of mechanics is more important, leading to critical slip curves that cluster around the classical slip curve for a homogeneous medium, regardless of the random field realization. Ching et al. [9] called these critical slip curves "constrained". The authors demonstrated by simulated examples that the mobilized shear strength can be adequately represented by a spatial average defined over a classical slip curve or a domain that includes this curve. This is evident, because this domain does capture the range of constrained critical slip curves reasonably well, even though the medium is not homogeneous. For problems where the critical slip curves are attracted by the location and persistence of weak zones, these curves are more scattered because the distribution of weak zones changes from realization to realization. A

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spatial average defined over a fixed prescribed domain, specifically one containing the classical slip curve, is not well correlated to the mobilized shear strength for the converse reason.

By definition, the critical slip curve is the weakest slip curve among potential slip curves. Therefore, the mean value for the mobilized shear strength should be less than the mean value of the random field [21,5,6,10]. An important parameter that affects the trajectory of the critical slip curve is the scale of fluctuation (SOF). From a physical viewpoint, the SOF controls the degree of persistence in weak or strong zones. For example, if the SOF in the horizontal direction is infinite, a weak zone at a particular depth will manifest itself as an entire layer, rather than a finite length lens. The thickness of this weak layer is related the SOF in the vertical direction, but this is a secondary factor compared to the horizontal persistence in the form of an extended layer for problems dominated by a horizontal sliding mechanism. Surely, the critical slip curve would be attracted to pass through this weak layer if its strength is sufficient weak and if it lies within the influence zone of the geotechnical structure, subject to mechanical constraints.

Related to this, a phenomenon called a "worst case SOF" was observed in the literature for capacity problems: more complex plastic zones (non-classical failure mechanisms) can occur when SOF is comparable to some multiple of the characteristic length of the structure (e.g., height of slope, diameter of tunnel, depth/width of excavation). The complex behavior typically manifests itself most clearly when the mean response (e.g., mean bearing capacity) from random realizations is compared with the nominal response (e.g., nominal bearing capacity) produced by a soil mass taking mean properties everywhere. At the worst case SOF, the mean response is worse than the nominal one (e.g., mean capacity < nominal one). Moreover, the worst case SOF refers to the SOF where the discrepancy between the mean response and the nominal response is the largest. Table 1 shows the worst case SOFs reported in previous studies.

Luo et al. [33] and Wu et al. [46] concluded that mean factor of safety for basal heave is the same as the nominal FS probably because in their analyses the critical slip curve is assumed to be a prescribed slip curve. This assumption can be unconservative because in reality the trajectory of the critical slip curve depends in part on the strength distribution in each random field realization. There are two objectives for the current study:

1. To clarify the degree of unconservative error incurred by the simplistic *prescribed* slip curve hypothesis, and to illustrate the existence of the phenomenon of a worst case SOF in basal heave analysis. Random finite element method (RFEM) is adopted to simulate the basal heave factor of safety (FS) for excavations in soft clays. In RFEM, the critical slip curve emerges correctly as the *solution* of a boundary value problem in a spatially variable soil. Therefore, it is not a prescribed curve. The phenomenon of a worst case SOF will be demonstrated by RFEM.
2. To develop a simplified probabilistic model based on the "weakest path hypothesis" for the mobilized s_u that can reproduce the mean and coefficient of variation of FS without RFEM, i.e. without simulation and finite element analysis. In particular, it will be shown that this weakest path model can reproduce the phenomenon of a worst case SOF, both qualitatively and quantitatively. The 5% quantile of this mobilized strength can be adopted as the characteristic value in design.

The concept of a worst case SOF is very important in reliability-based design (RBD), e.g., the existence of a worst case SOF in the reliability-based resistance factor has been recently demonstrated by Fenton et al. [23]. The reason is that it is usually difficult to get a robust estimate of SOF from limited soil data. In the absence of an estimate for SOF, it is conservative to use the worst case SOF in RBD under this situation. In the presence of sufficient data, one can attempt to estimate a more realistic value of SOF, rather than adopt the data-independent worst case SOF. Nonetheless, it is worth pointing out that statistical characterization of random field parameters (which includes SOF) is not straightforward and one should be mindful of the considerable statistical uncertainties involved [11,15]. The first objective of this paper demonstrates that the assumption of a prescribed slip curve is overly simplistic, because it cannot capture the phenomenon of a worst case SOF, which is important to RBD. However, it is significantly more costly to adopt RFEM in design. The second objective explores the possibility of adopting a less costly "weakest path" model that does not over-simplify the problem to such an extent that the worst case SOF feature is lost. The resulting probabilistic model for the mobilized shear strength is of practical significance, because its 5% quantile is equal to the characteristic value specified by Eurocode 7. The calibration of the "weakest path" model is illustrated using one excavation example.

Table 1
Worst case SOFs reported in previous studies.

Study	Problem type	"Worse case" definition	Characteristic length	Worst case SOF
Jaksa et al. [30]	Settlement of a nine-pad footing system	Under-design probability is maximal	Footing spacing (S)	1 × S
Fenton and Griffiths [19], Soubra et al. [36]	Bearing capacity of a footing on a c-ϕ soil	Mean bearing capacity is minimal	Footing width (B)	1 × B
Fenton et al. [22]	Active lateral force for a retaining wall	Under-design probability is maximal	Wall height (H)	0.5 ∼ 1 × H
Fenton and Griffiths [20]	Differential settlement of footings	Under-design probability is maximal	Footing spacing (S)	1 × S
Breysse et al. [4]	Settlement of a footing system	Footing rotation is maximal	Footing spacing (S)	0.5 × S
		Mean different settlement between footings is maximal	Footing spacing (S) Footing width (B)	f(S,B) (no simple equation)
Griffiths et al. [26]	Bearing capacity of footing (s) on a ϕ = 0 soil	Mean bearing capacity is minimal	Footing width (B)	0.5 ∼ 2 × B
Vessia et al. [45]	Bearing capacity of footing on c-ϕ soil	Mean bearing capacity is minimal (anisotropic 2D variability)	Footing width (B)	0.3 ∼ 0.5 × B
Ching and Phoon [5], Ching et al. [10]	Overall strength of a soil column	Mean strength is minimal	Column width (W)	1 × W (compression) 0 × W (simple shear)
Ahmed and Soubra [1]	Differential settlement of footings	Under-design probability is maximal	Footing spacing (S)	1 × S
Hu and Ching [29]	Active lateral force for a retaining wall	Mean active lateral force is maximal	Wall height (H)	0.2 × H
Studlein and Bong [37]	Differential settlement of footings	Under-design probability is maximal	Footing spacing (S)	1 × S
Ali et al. [2]	Risk of infinite slope	Risk of rainfall induced slope failure is maximal	Slope height (H)	1 × H