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Plasticity modeling of liquefaction effects under sloping ground and irregular cyclic loading conditions

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ABSTRACT

The formulation of the constitutive model PM4Sand [7] is modified to improve simulations of liquefaction-induced deformations of sloping ground subjected to uniform and irregular cyclic loading. Existing laboratory test data on the response of liquefiable sand under sloping ground conditions subjected to uniform cyclic loading are reviewed and additional experimental data from undrained cyclic direct simple shear (DSS) tests of liquefiable sand under sloping ground conditions subjected to irregular cyclic loading are presented. The previous version of the PM4Sand model (Version 2) and its limitations in modeling liquefaction effects in sloping ground with uniform and irregular cyclic loading are described. Evidence from the laboratory tests show that it is the effect of loading history on the dilation and stiffness characteristics of the response that is not properly captured by Version 2 of the model. The modifications made in Version 3 include a revised dependency of dilation and plastic modulus on the fabric tensor and its history. These modifications are introduced using irregular cyclic DSS test results to illustrate the motivations for the changes in the constitutive equations. Finally, two examples of calibration are presented: one against a specific laboratory test result for a single sand and one against an engineering correlation describing trends observed for many sands across a broader range of relative densities, confining stresses, and loading conditions. The updated formulation in Version 3 of the model is shown to better approximate liquefaction behaviors for sloping ground and irregular cyclic loading conditions.

1. Introduction

Numerical simulations are often used for estimating liquefaction-induced ground deformations and associated damages of soil and soil-structure systems subjected to earthquake loading. The accuracy of such simulations depends, in part, on the ability of the constitutive model to approximate liquefaction behaviors in the presence of the static shear stresses imposed by sloping ground or overlying structures in combination with the irregular cyclic loading imposed by earthquake shaking.

Ziotopoulou et al. [22] examined several constitutive models for liquefiable soils and concluded that most had notable limitations in their ability to simulate the effects of sloping ground conditions on pore pressure and shear strain generation for the full-range of relative densities (D_R), initial static shear stress ratios (α), and vertical effective confining stresses (σ'_{vc}) important to practice. Furthermore, it was found that the ability to simulate liquefaction behaviors under sloping ground conditions could not necessarily be improved by calibration of the model parameters, which indicates that the simulated behaviors are controlled by the underlying functional forms of the constitutive equations. This means that improving the ability of a constitutive model to approximate behaviors under sloping ground conditions may require changes to the functional forms of the constitutive equations. One such example in the advancement of a constitutive model was the revision of UBCSAND by Beaty and Byrne [2] to improve its response under sloping ground conditions.

The constitutive model examined herein is the bounding surface plasticity model PM4Sand, the second version of which is described in Boulanger and Ziotopoulou [7] and Ziotopoulou and Boulanger [21]. Single-element direct simple shear (DSS) simulations showed that PM4Sand (Version 2) has limitations in its ability to approximate the effects of sloping ground conditions on the cyclic strength during uniform cyclic loading for the range of D_R and σ'_{vc} explored [6,22]. Application of the model in the analysis of a centrifuge test incorporating a submerged slope of loose sand subjected to an irregular input motion [13] showed that PM4Sand

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Version 2 tended to over-estimate the accumulation of shear strains under sloping ground conditions during irregular cyclic loading. The above limitations were attributed to inherent limitations in the constitutive equations of the model.

This paper summarizes modifications to the constitutive model PM4Sand to improve simulations of liquefaction-induced deformations of sloping ground subjected to uniform and irregular cyclic loading, while maintaining reasonable behaviors for a range of other loading conditions important to earthquake engineering applications. The first section of the paper describes expected soil behaviors based on (1) a review of experimental data on the response of liquefiable sands under sloping ground conditions subjected to uniform cyclic loading and (2) additional experimental data from undrained cyclic DSS tests of sand under sloping ground conditions subjected to irregular cyclic loading. The second section introduces the PM4Sand model and describes the limitations of the Version 2 in modeling liquefaction effects in sloping ground with uniform and irregular cyclic loading. Evidence from the laboratory tests show that it is the effect of loading history on the dilation and stiffness characteristics of the response that are not properly captured by Version 2 of the model. The modifications made in Version 3 include revised dependency of dilatancy D and plastic modulus K_p on the fabric tensor and its history. These motivations for the modifications to the constitutive equations are illustrated using the results of the DSS tests with irregular cyclic loading. The third section presents two examples of calibration for sloping ground conditions with irregular undrained cyclic loading: one against a specific laboratory test result for a single sand and one against engineering correlations describing trends observed for many sands across a broader range of D_R, σ'_{vc}, and loading conditions. For both examples, the calibration process is also constrained by the requirement that the model maintain reasonable approximations of other undrained and drained, monotonic and cyclic, loading behaviors important to earthquake engineering applications, as described in Boulanger and Ziotopoulou [8]. The updated formulation in Version 3 of the model is shown to better approximate liquefaction behaviors for sloping ground and irregular cyclic loading conditions.

2. Experimental data on the response of liquefiable soils under sloping ground conditions

2.1. Uniform cyclic loading

Saturated sands within sloping ground respond differently to seismic loading than sands under level ground. The presence of initial and sustained static shear stresses (τ_{st}) within sloping ground is the factor that causes this difference, having strong effects on the pore pressure and shear strain (γ) generation behavior. During seismic loading, the same elements are subjected to the additional cyclic shear stress (τ_{cyc}) from the shear waves that are propagating in the deposit. The superposition of τ_{st} and τ_{cyc} can have a significant effect on the response of the soil, with the net effects depending on D_R, confining stress, and the relative magnitude of the two shear stresses which determines whether there are shear stress reversals or not.

There is a large body of experimental data by various researchers describing the undrained cyclic loading behavior of saturated sands under an initial τ_{st} using cyclic triaxial, cyclic simple shear, torsional shear, and torsional ring shear devices. The magnitude of an initial τ_{st} in such tests is often expressed in terms of the static shear stress ratio $\alpha\ (=\tau_{st}/\sigma'_{vc})$ which is the ratio of the τ_{st} to the effective consolidation stress σ'_{vc} on the plane of interest. The effect of α on the soil's cyclic resistance ratio (CRR) is then often expressed in terms of a K_α factor [15] as:

$$K_\alpha = \frac{CRR_\alpha}{CRR_{\alpha=0}} \tag{1}$$

where CRR refers to the cyclic stress ratio ($CSR = \tau_{cyc}/\sigma'_{vc}$) required to trigger liquefaction (according to the specified failure criterion which for this work was a peak γ=3%) in a specified number of uniform loading cycles; CRR_α is the CRR value for a given value of α; and $CRR_{\alpha=0}$ is the CRR value when α=0 (level ground). Experimental results on a range of sands at confining stresses less than about 300 kPa showed that CRR would tend to decrease with increasing α for loose sands and tend to increase with increasing α for dense sands; these trends are illustrated in Fig. 1a showing CRR values from simple shear test results by Vaid and Finn [20] for Ottawa sand tested at D_R of 50% and 68% with σ'_{vc} = 202 kPa, and in Fig. 2a summarizing ranges of K_α values observed for various sands across three ranges of D_R at confining stresses less than about 300 kPa [11]. Experimental

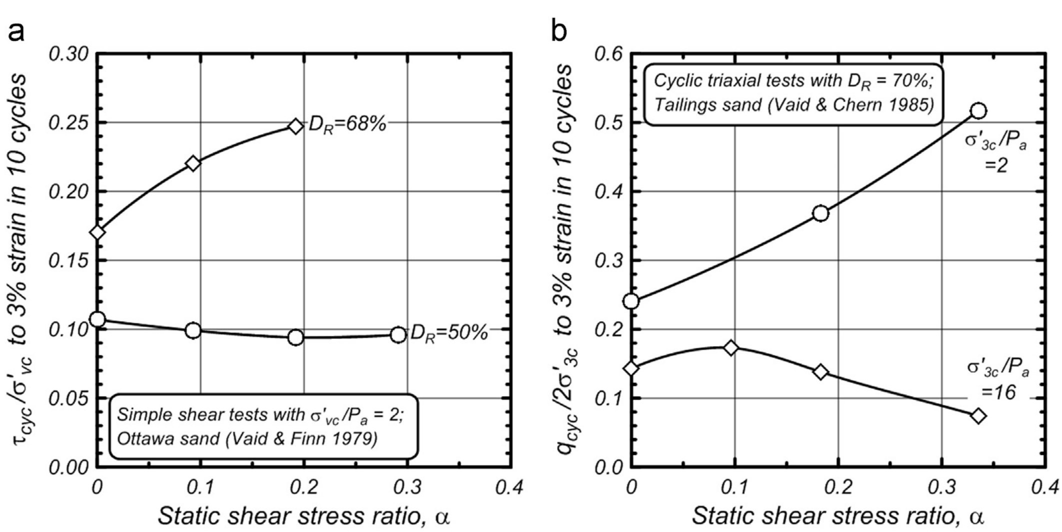

Fig. 1. Variation of the CRR for 3% shear strain in 10 cycles with the initial static shear stress ratio, α. Graph (a) shows the effect of varying the relative density D_R, and graph (b) shows the effect of varying the effective consolidation stress σ'_{vc}.