A Coupled Unified Elastoplastic Model of Soil, Based on Bounding Surface Theory in Saturated and Unsaturated States

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ABSTRACT

Soils in nature can variably be in dry, saturated, or unsaturated conditions. In geotechnical projects, all three soil states must be considered, because soil states can be changed by environmental effects. The most elastoplastic models in soil mechanics were developed for saturated conditions. In this paper, a unified model, in a critical state framework is presented for describing the behavior of a large spectrum of soils under monotonic loading in drained and undrained conditions based on bounding surface theory and the nonassociated flow rule. To unified the simulation of both clayey and sandy soils, among phase transformation behavior, in this model, a modified general dilatancy rule is used. In the current model, an effective stress approach is used that can easily consider both saturated and unsaturated states through effective stress parameter dependent on suction value. The proposed model considered the coupling effect of mechanical and water retention behaviors using soil water characteristic curve dependent on void ratio. To improve model accuracy and convergence, an implicit numerical integration scheme is used to implement the model. Using the experimental data available in the literature, numerical model predictions were shown to be in good agreement with the experimental results. The results showed that the proposed model was able to predict the characteristic features of the behavior of a wide range of soils, including smooth transition behavior from elastic to a plastic state, stress softening and hardening, strain dilatancy, and also phase transformation behavior.

KEYWORDS

Unified Model, Saturated and Unsaturated Soils, Bounding Surface, Effective Stress, Hydromechanical Coupling Effect.

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1. Introduction

In soil mechanics, soils are divided into three states dry, saturated, and unsaturated soils. The difference between these conditions is their pore space saturation, if pore space is only filled with air or water, it is dry and saturated states respectively. If pore space is filled with a combination of air and water, the soil state is unsaturated and it is noted that air and water are the most common fluids in soil media. Constitutive models in soil mechanics are mostly developed for saturated soils and as the importance and need for prediction of a larger spectrum of soil behavior have been specified, unsaturated soil mechanics is established. On the other hand, most of the constitutive models can accurately simulate only clayey or sandy soil behavior, and the need for elastoplastic models that can simulate the behaviors of a large spectrum of soils including both clay and sand, in a unified framework is necessary.

2. Methodology

In this research, a saturated elastoplastic model extended to an unsaturated state using an effective stress approach. Triaxial stress state for representation of soil effective stress is described using mean effective stress and deviatoric stress and their conjugated strain components of work input in thermodynamics, including the volumetric strain of soil skeleton and deviatoric strain.

In the current model, bishop's stress [1] is used for effective stress relation that expressed as Eq. (1):

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma}_{net} + \chi s \boldsymbol{\delta} \qquad (1)$$

Where $\boldsymbol{\sigma}_{net}$ is net stress, χ is effective stress parameter depends on suction and volumetric strain, s is matric suction and δ is kronecker delta.

In this research, effective stress parameter proposed by Khalili and Khabbaz [2] based on shear strength test data for a wide range of soils, is used, this relation is expressed in Eq. (2):

$$\chi = \begin{cases} 1 & for\ s < s_e \\ \left(\dfrac{s_e}{s}\right)^{\Omega} & for\ s \geq s_e \end{cases} \qquad (2)$$

Where s_e is corresponding suction value in transition from saturated to unsaturated state and vice versa and Ω is material parameter with best fit value of 0.55.

A unified constitutive model for describing a large spectrum of soil behavior in both saturated and unsaturated conditions under monotonic loading is proposed. For this purpose bounding surface plasticity theory, critical state and limiting isotropic compression line concepts, modified dilation rule, and suction hardening rule, were used. Bounding and loading surfaces, current stress point, and its image point on bounding surface and surface size ratio, is shown in Figure 1.

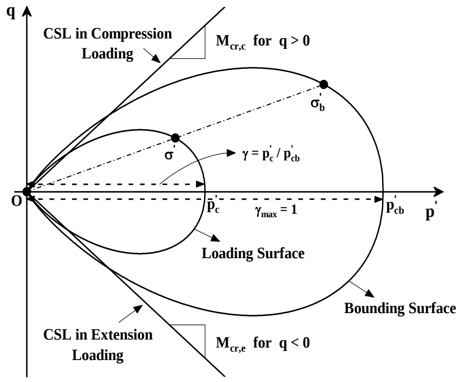

Figure 1 Schematic of the bounding, loading surfaces, and mapping rule, with surfaces size ratio

The coupled effect of mechanical and water retention behavior, hydraulic hysteresis, and evolution of soil water characteristic curve (SWCC) dependency on void ratio is considered in a unified framework. An implicit numerical integration scheme is used for the implementation of the constitutive model. Implementation of implicit integration method in the current model has two stages, elastic state predictor stage, and plastic corrector stage. In this approach, when the stress state moves beyond the bounding surface, it returns to the bounding surface automatically without the need for any improvement technique and correction. By satisfying the equilibrium equation, isotropic and suction hardening, surfaces size ratio evolution rule, effective degree of saturation variation, and consistency condition, the stress state should always lie on the loading surface, therefore loading surface should be consistent with the current stress state. Finally, simultaneous satisfying of these conditions results in nonlinear system of equations that according to the nonlinearity of the system of equations, the intended system of equations is solved using the Newton-Raphson method.

The validity and efficiency of the proposed model are shown by a comparison of simulation results and experimental data.

3. Results and Discussion

To simulate soil behavior in the current model under monotonic mechanical and hydraulic loadings and also drained and undrained conditions, the model needs 12 parameters in the saturated state and 6 other parameters related to SWCC in the unsaturated state.

To investigate the current model ability and efficiency for simulating saturated and unsaturated soil behavior under monotonic loading in drained and undrained conditions, the results of model simulation for clayey and sandy soils are presented. For verification, many experimental tests on London clay, Guiyang clay, Hostun sand, and Ottawa sand at the saturated state and also on Pearl clay, and Kurnell sand at the unsaturated state, are simulated and compared with experimental data. Two tests of unsaturated clayey and sandy soils are shown here for example.

Model predictions were investigated to simulate unsaturated clay in drained and undrained conditions, using presented experimental data [3, 4] on Pearl clay soil. In Figure 2 model simulation results are shown in comparison with experimental results of triaxial compression and wetting tests.

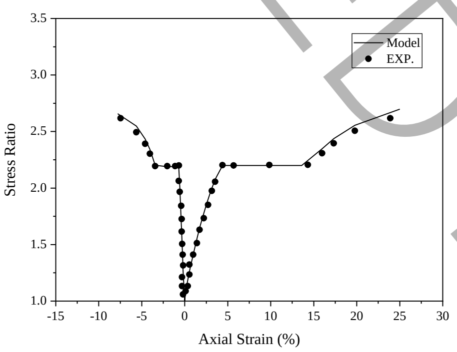

Figure 2 Comparison of model simulation results with experimental data of unsaturated Pearl clay under triaxial compression and wetting loadings

Model predictions were investigated to simulate unsaturated sand in drained and undrained conditions, using presented experimental data [5] on Kurnell sand soil. In Figure 3 model simulation results are shown in comparison with experimental results of drained triaxial compression tests.

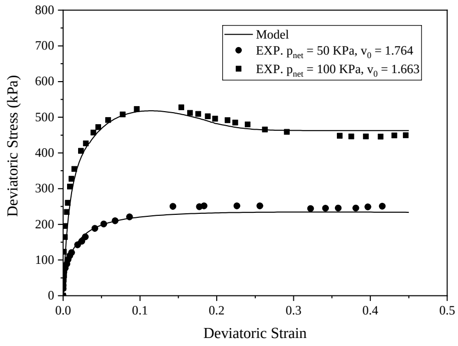

Figure 3 Comparison of model simulation results with experimental data of unsaturated Kurnell sand under drained triaxial compression loading

As shown in Figures 2 and 3, the model predicted experimental results accurately and model simulation results had good agreement with experimental results. Stress-strain and water retention behaviors of soil samples predicted by the current model, not only at constant suction but under the wetting path.

4. Conclusions

In this study for unified simulation of elastoplastic behavior of a wide range of soils due to loading and unloading, bounding surface plasticity theory is considered, and also, critical state concept and limiting isotropic compression line are used. Both plastic volumetric strain and matric suction have been introduced as hardening parameters. The coupled effect of flow and deformation fields is considered using effective stress parameter and soil water characteristic curve. Special attention has been paid to the interaction between effective stress and drying and wetting paths in an unsaturated state. In the current model, the considered procedure for predictions of volume change dependency of soil water characteristic curve, there is no need to define a new and additional material parameter, and only the soil water characteristic curve at reference void ratio is needed. By continuous correction and revision of soil water characteristic curve with void ratio increment and identifying a new hydraulic state of the soil, the model can predict the full experienced hydraulic path of soil during mechanical loading. Model basic abilities and features validated by comparison of simulation results with experimental data. The results showed the accuracy and validity of the proposed model in the simulation of hardening, softening, dilation, and collapse behaviors of both clayey and sandy soils in drained and undrained conditions at mechanical and hydraulic monotonic loadings.

5. References

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