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A Constitutive Model for Structured Soils Based on HISS Model and Disturbed State Concept

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ABSTRACT: The compression behavior of structured soils after virgin yielding is nonlinear that can not be captured by a single line in semi-logarithmic or fully-logarithmic stress-volumetric strain space. The natural or artificial structure of the soil retains the void ratio of the soil at higher levels than the void ratio of the same soil in remolded state at the same stress levels. Increasing the stress level from the threshold stress of the virgin yielding initiates the crashing of the soil structure that results in large amounts of volumetric strains with a small value of volumetric stiffness. Further crashing the structure of the soil and decreasing its void ratio increases the volumetric stiffness of the soil. Although this procedure is highly nonlinear, however it is a continuous phenomenon and can be formulated mathematically. Since the structure losing behavior of structured soils occurs between two known states, therefore, could be explained based on the disturbed state concept (DSC). According to the DSC, the behavior of complex phenomena between two reference states could be described based on their behaviors in two reference states using an appropriate state function. The state function or interpolating function relates the response of the material at any level to its responses at two reference states. In this paper, a constitutive model base on the hierarchical single surface model (HISS) and the disturbed state concept was proposed to describe the stress-strain and the failure behavior of structured soils. The behavior of the soil at the beginning of the virgin yielding was considered as initial, relatively intact (RI), state and its behavior after a fully crashed state was considered as fully adjusted (FA) state. The disturbance function is derived based on the isotropic compression behavior of the material in the laboratory. A power form state function was proposed to describe the variation of the bulk modulus of the soil. The variable compression model was implemented in HISS model to capture the volumetric behavior of the structured soil. The proposed model was verified based on the data from the literature. The verification of the proposed constitutive model showed the ability of the model to predict the stress-strain and failure behavior of structured soils.

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1- Introduction

Degradation of the structure of natural soils results in a highly nonlinear compression behavior. The inter-particle bonds of structured soils retain additional loads when compared to remolded soils. Breaking of these bonds reduces the stiffness and modulus of elasticity of the soil. Moreover, soils in nature on which real-life structures are constructed undergo different conditions from those of the same soils in laboratory settings. Some granular soils display brittle behavior under loads. After the destruction of the structure, further rise in the load pushes grains into each other, reducing voids and increasing the modulus of elasticity. The nonlinearity of the compression behavior is more significant for soils in nature as they are not disturbed and have granular structures. The consolidation behavior of structured soils is influenced by their structural fractures. Such soils show different strain variations below the fracture load compared to the condition after structural fracture at the same stress in the laboratory. Granular soils exhibit different stress-strain behavior under a wide loading range. The literature has reported that nonlinear behavior in crushing while continuity is the most important characteristic of natural soils. So, the DSC can be employed to describe the behavior of structured and brittle soils. According to the DSC, the behavior of a material between two known reference states can be described by a proper state function. A stress-based function between the two known reference states could be employed to describe the highly nonlinear behavior of structured soils. Thus, the behavior of brittle soils in each state and at any states between the known initial reference state (before structural fracture) and the ultimate reference state (after complete fracture) and can be described using a stress-dependent state function. The present study formulates the variable modulus of elasticity using the disturbance state concept by a stress-based function[1.2]

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2- Methodology

DSC is grounded on the idea that the reaction of an object can be described based on the mutual reactions of its components. In other words, external forces change the current state into a new equilibrium state by changing objects. In practice, complete adaptation to the new conditions may not be measurable. However, the initial behavior of materials is observable, and the ultimate ideal state could be estimated by the observed behavior of the material. The behavior of the structured soil in DSC framework consists of two references or a combination of the two references, including a relative intact (RI) section and a fully adjusted (FA) section. The latter describes the behavior of the soil in a fully crashed state. The behavior of a material can be described by disturbance parameter D and function Fi between the RI and FA reference states. Eq. (1) represents the behavior of materials at a given time between the reference states using the disturbance parameter D which acts as an interpolating parameter connecting the two reference states.

$$F_i = (1 - D) RI + D\, FA \quad (1)$$

The yield function on the HISS model is :

$$F = \bar{J}_{2D} - \left(-\alpha \bar{J}_1^{\,n} + \gamma \bar{J}_1^{\,2}\right)(1 - \beta S_r)^m = 0 \quad (2)$$

2- 1- Compressibility behavior of brittle soils based on DSC

Figure 1 illustrates the compressibility behavior of soils with a variable elastic modulus. The formulation to determine the disturbance state parameter is described below.

In Figure 1, K_{RI} is the bulk modulus at the beginning of structural fracture, K_{FA} is the bulk modulus at the end of the test, P'_0 is the initial stress, and P'_r is the confining pressure at the beginning of the virgin yielding. The disturbance function should be obtained using experimental results or mathematical analyses. The compressibility index has completely nonlinear variations in the compaction of structured soils; that in the logarithmic scale, it is nonlinear at the beginning of loading and linear at the end of loading. Therefore, the slope of the volumetric compression curve in the semi-logarithmic scale could be described based on DSC as:

$$\frac{\lambda - \lambda_{FA}}{\lambda_{RI} - \lambda_{FA}} = e^{\chi} \left(e^{-\left(\chi \frac{p'}{p'_r}\right)} \right) \quad (3)$$

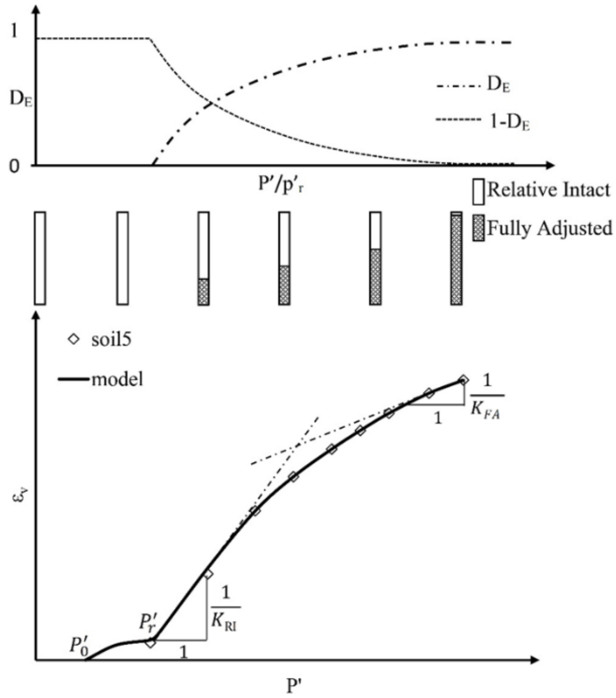


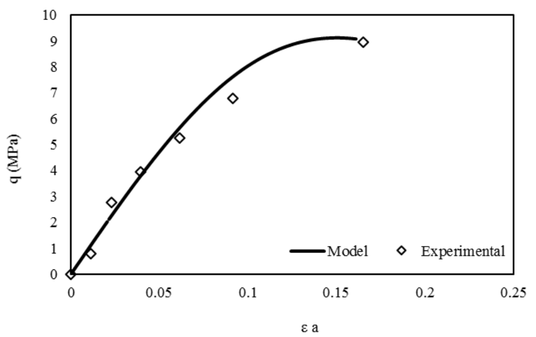
Fig. 1. Representation of relatively intact (RI) and fully adjusted (FA) states for structured soils

In which λ is the volumetric compressibility index of the soil in the semi-logarithmic scale. Since the formulations are based on the elastic modulus in the HISS model, the parameters λ and E are related using the existing equations to calculate the disturbance parameter based on the elastic modulus. E and K are related as:

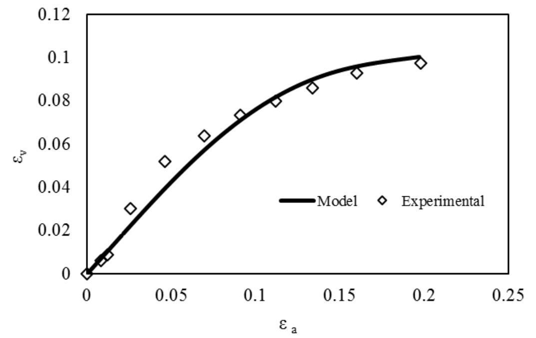
$$k = \frac{E}{3(1 - 2\nu)} \quad (4)$$

Where E is the elastic modulus, ν is Poisson's ratio for the soil, and K is the bulk modulus. According to Eq. (4), K and E have a direct relationship. As can be seen in Fig. 1, K rises as loading continues. In other words, further fracture completion increases the elastic modulus as the void ratio decrease. K and λ are related as [3]:

$$\frac{\lambda}{(1 + e_0) P_0} = \frac{1}{K} \quad (5)$$



(a) axial strain–deviatoric stress



(b) axial strain–volumetric strain

Fig. 2. Results of a drained triaxial test on Corinth Canal marls (Soil5)[1]

Table 1. Model Parameters for Reference Soil

Name	Type of soil	χ	P'_r (mPa)	E_{RI} (mPa)	E_{FA} (mPa)
Corinth Canal marls (Soil.5)	Structured	1	3.8	120	150

Based on Eqs.(4) and (5), Eq. (3) can be rewritten as :

$$\frac{E - E_{FA}}{E_{RI} - E_{FA}} = e^{\chi}\left(e^{-\left(\chi \frac{p'}{p'_r}\right)}\right) \quad (6)$$

Finally, given Eq. (1) based on the elastic modulus:

$$\begin{cases} E_i = (1-D)E_{RI} + DE_{FA} \\ D = 1 - \left(e^{\chi}\left(e^{-\left(\chi \frac{p'}{p'_r}\right)}\right)\right) \end{cases} \quad (7)$$

3- Result and Discussion

Figure 2 shows the results of the fine-grained structured soil. Table 1 presents the model parameters for this soil

This study proposed a structured model for the nonlinear volume compressibility behavior (variable elastic modulus) of soils based on confining pressure. As can be seen in Figure 2, the model was able to predict the behavior of soils with sufficient accuracy.

4- Conclusion

The present study proposed a model to investigate the compression behavior of brittle soils using DSC. A power equation based on confining pressure, structural destruction, and brittle behavior was introduced and applied to the HISS model. A variable modulus of elasticity was described for structured soils under loading due to stress variations and structural destruction in order to calculate the elastic modulus at any time during destruction or the crushing of soil grains using the disturbed state. This variable parameter was incorporated into the HISS model to analyze the behavior of such soils. Hence, it can be employed in numerical calculations. The proposed model could be employed to describe the stress-strain and failure behavior of a wide range of geomaterials. Verification of the results of the proposed model with the experimental data demonstrated the performance and accuracy of the model

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