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Revising the unified hardening model by using a smoothed Hvorslev envelope

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The original unified hardening (UH) model, in which a straight Hvorslev envelope was employed to determine the potential peak stress ratio of overconsolidated soils, is revised using a smoothed Hvorslev envelope (Hermite-Hvorslev envelope). The strength at the intersection between the straight Hvorslev envelope and the critical state surface (i.e. Mohr-Coulomb envelope) can be undefined due to the discontinuous change in the slope of the two linear strength envelopes mentioned above. A smoothed Hvorslev envelope is derived through Hermite interpolation to ensure a smooth change between the proposed Hvorslev envelope and the zero-tension surface as well as a smoothed transition between the proposed Hvorslev envelope and the critical state surface. The Hermite-Hvorslev envelope is then integrated into the original UH model, and then the UH models with four different functions of the Hvorslev envelope are compared with each other. The UH model revised by the Hermite-Hvorslev envelope can well predict the mechanical behaviors of normally consolidated and overconsolidated soils in drained and undrained conditions with the same parameters in the modified Cam-Clay model.

1. Introduction

Most clays encountered in geotechnical engineering are subjected to a preconsolidation pressure higher than the current pressure and, therefore, are overconsolidated to some extent because of human activities (such as compaction, excavation, and tillage) and changes in the environmental loads (such as landsides, rainfall/evaporation, and fluctuations of groundwater level). Theoretically, although soils are separated into normally consolidated and overconsolidated soils, overconsolidated soils are more general because normally consolidated soil can be regarded as a special case of overconsolidated soil with an overconsolidation ratio (OCR) equal to one. Soil behaves differently because of the variation in the OCR value, which has been reported in many experimental results (Banerjee and Stipho, 1979; Nakai and Hinokio, 2004). Normally consolidated soil exhibits a monotonically increasing stress ratio that will approach a constant contractive volume change during shearing. On the other hand, overconsolidated soil with an OCR greater than one may exhibit a peak stress ratio and post-peak softening behavior subjected to shearing, both of which become more distinct with increasing OCR. In addition, compared with normally consolidated soil, overconsolidated soil may show a dilative volume change after volume contraction during shearing. The shearing related volume dilation can be more distinct due to the increase in the OCR value. In isotropic stress conditions, overconsolidated soil is less compressive (i.e. stiffer) compared with the normally consolidated soil with the identical initial stress, and the stiffness of the overconsolidated soil gradually increases with an increase in the OCR.

The modified Cam-Clay model is successful in modeling the mechanical behaviors of normally consolidated and lightly overconsolidated clays (usually the OCR is less than 2), such as the critical state and volume contraction caused by shearing. However, it is not suitable for reproducing the mechanical responses of medium or heavily overconsolidated clays, such as the peak strength, post-peak softening and shear-dilation. Therefore, based on the modified Cam-Clay model, a number of approaches have been proposed to interpret and simulate the typical mechanical behaviors of overconsolidated soils, especially to build a unified constitutive framework to describe the continuous behavior change of soils for the entire range of the OCR (from 1 to infinite). For example, Pender (1978) proposed a semi-empirical but practical

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constitutive model for overconsolidated soils based on three hypotheses on the yield surface (f), potential surface (g) and hardening function (h), using experimental observations. Mröz et al. (1978) employed a set of nesting surfaces in the stress space in addition to the yield surface to specify the variation of the 'hardening moduli field', during the deformation process with complex loading programs involving loading, unloading and cycle loading. Based on the concept of nesting surfaces, Dafalias and Herrmann (1986) introduced the 'bounding surface plasticity' and then applied the radial mapping version of the bounding surface plasticity to modeling the mechanical behaviors of overconsolidated clayey soils. The bounding surface plasticity was also included in the MIT-E3 model (Whittle and Kavvadas, 1994) to reproduce the irrecoverable, anisotropic and path-dependent behavior of overconsolidated clays with an OCR less than eight. Ling et al. (2002) incorporated rotational and distortional hardening rules into the bounding surface formulation with an associated flow rule to predict the mechanical behavior of anisotropically overconsolidated clays. Morvan et al. (2010) extended bounding surface plasticity from saturated overconsolidated soils to unsaturated overconsolidated soils. On the other hand, based on the concept of nesting surfaces, Hashiguchi (1980) extended the concept of a yield surface to the sub-yield state under the distinct yield state and assumed the existence of a 'sub-loading surface' in the sub-yield state. Nakai and Hinokio (2004) developed a constitutive model based on the sub-loading surface plasticity to simulate the typical deformation and strength behavior of normally consolidated and isotropically overconsolidated clays in general stress conditions. Most recently, Zhou and Sheng (2015) developed a hydro-mechanical coupled constitutive model for unsaturated overconsolidated soils based on the sub-loading surface plasticity. However, most of these models have limited engineering applications due to the large number of model parameters. Some of these model parameters, as noted by Yao et al. (2012), are difficult to be calibrated through conventional laboratory tests, and their values can often only be determined by a trial-and-error method.

For engineering applications, Yao et al. (2008a, 2009) proposed a robust elastoplastic model to interpret the mechanical behaviors of both normally consolidated and overconsolidated soils based on the sub-loading surface concept, the straight Hvorslev envelope and the unified hardening (UH) parameter (Yao et al., 2007, 2008b). The proposed model, referred to as the original UH model, is simple and practical because it only includes one additional parameter (i.e. the Hvorslev slope) compared with the modified Cam-Clay model. Yao et al. (2012) replaced the original straight Hvorslev envelope by a parabolic one with an initial slope of less than 3 to avoid unrealistic implications in the original UH model because the zero-tension surface is not included. It was employed in developing time-dependent UH model (Yao et al., 2015). However, it is subjective to assume that the Hvorslev envelope must be expressed by an ad hoc parabolic function without justification. Therefore, Yao and Zhou (2013) used the piecewise Hvorslev envelope (i.e. a combination of the zero-tension line and the straight Hvorslev envelope) when they extended the original UH model from isothermal to non-isothermal conditions. However, with respect to all three UH models, the Hvorslev envelope (straight, parabolic and piecewise) cannot join into the critical state line (i.e. Mohr-Coulomb envelope) smoothly. In other words, the slope of the strength envelope is not continuous at the intersection (i.e. a singularity point) between the Hvorslev envelope and the Mohr-Coulomb envelope. Such a discontinuity in the slope means that the strength cannot be defined at this singular point when, for example, Mohr circles are adopted to interpret the strength of soils. This problem will be discussed in detail in the next section.

In this paper, Hermite interpolation is employed to smooth the transition between the Hvorslev envelope and the zero-tension line as well as the transition between the Hvorslev envelope and the critical state line without additional parameter. The proposed smoothed Hvorslev envelope, which is referred to as Hermite-Hvorslev envelope, will be used to replace the straight Hvorslev envelope which was employed in the original UH model. The UH model revised with the Hermite-Hvorslev envelope will be compared with the original UH model, the UH model with a parabolic Hvorslev envelope and the piecewise Hvorslev envelope. The revised UH model with the Hermite-Hvorslev envelope can well predict the mechanical behaviors of normally consolidated and overconsolidated soils using the same parameters in the modified Cam-Clay model. Finally, drained and undrained triaxial test results from the literature are used to validate the revised UH model with the Hermite-Hvorslev envelope.

2. Hvorslev envelope and strength singularity

In geometry, an 'envelope' of a family of curves in the plane is defined as a curve that is tangent to each member of the family at some points. The Hvorslev envelope is an envelope of a series of Mohr circles at the peak condition for overconsolidated soils and was initially proposed based on the regression of the results from direct shear tests. In addition, as shown in Fig. 1, the Hvorslev envelope is usually associated with the Mohr-Coulomb strength envelope to describe continuous change in the shear strength (τ) for the entire range of the OCRs. It is commonly assumed that the Hvorslev envelope is a straight line with a smaller slope compared with the Mohr-Coulomb envelope (see Fig. 1). Therefore, the Mohr

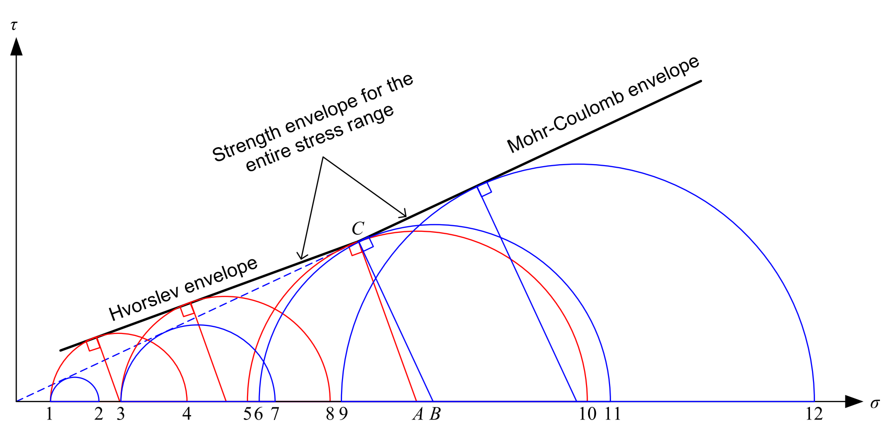

Fig. 1. Interpreting shear strength using Mohr circles, the straight Hvorslev envelope and the Mohr-Coulomb envelope.