Applied Ocean Research 76 (2018) 211–220

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Elasto-plastic model of structured marine clay under general loading conditions

Shuo Zhang, Guanlin Ye*, Chencong Liao, Jianhua Wang

Department of Civil Engineering and State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Keywords:
Elasto-plastic model
Soil structure
Superloading surface
Intermediate principal stress
Transformed stress space

ABSTRACT

In this paper, we propose an isotropic hardening elastoplastic model for structured marine clay that can describe its strength and deformation behavior under general loading conditions. A series of drained true triaxial tests were performed on structured and remolded marine clay to investigate the effect of intermediate principal stress. The test results show that the intermediate principal stress has a considerable effect, not only on the strength, but also on the deformation behavior of marine clay. A modified stress-dilatancy equation is defined in transformed stress space to capture this feature. Then, the model is extended to consider the influence of structure by incorporating the superloading surface concept. Compared with the modified Cam-Clay model, the proposed model requires only two additional parameters, which can be determined conveniently from triaxial and oedometer tests. The proposed model was validated by performing undrained triaxial tests and drained true triaxial tests at various confining stresses and Lode angles, respectively, on remolded and structured clay.

1. Introduction

Marine clay is often encountered in ocean geotechnical engineering [1–8] and forms one of the typical strata in the shallow range of deep-water seabeds. Such clays have high water content and low shear strength. Clay strata contain natural depositional clay with a void ratio that is maintained at a higher level than that of remolded clay, because of the extra strength provided by the structure of the natural soil. Degradation of the initial structure has a considerable influence on the stress-strain response of natural clay [9–11]. In present numerical analyses of coastal infrastructure, soil is often described as a simple elastic-perfectly plastic material [12–14]. This assumption may be unsuitable for describing the structure of natural clay, and such a difference may significantly affect the design and construction of infrastructure [15]. Furthermore, since most geotechnical problems are three-dimensional, neglecting the influence of intermediate principal stress may lead to inaccurate predictions of soil response. Accordingly, a sophisticated model that can accurately describe the mechanical behavior of structured marine clay under general loading conditions would have a high practical value.

A variety of models have been proposed for modeling the structure and destructuration of natural clay. They are usually based on a model that can evaluate the behavior of remolded clay. Liu and Carter [16,17] presented a structured Cam-Clay model by incorporating the influence of soil structure into the modified Cam-Clay model. The influence of structure is considered according to the additional void ratio, which is the different in structured soil from its corresponding reconstituted soil at the same stress state with regard to void ratio. The destructuration of soil is described as a reduction of the additional void ratio. Zhu and Yao [18] adapted a three-dimensional unified Harding model (UH model) [19,20] to a structured UH model by introducing a moving normal compression line. Asaoka et al. [21,22] introduced the superloading yield surface concept to describe the mechanical behavior of structured soils. The effect of structure is simply defined as the size ratio of the superloading yield surface and the Cam-Clay yield surface. The measurement of destructuration is described by the reduction of the size ratio. Baudet and Stallebrass [23] presented a constitutive model for structured clay based on a reconstituted clay model. The measurement of destructuration is described by the relationship between change in plastic strain and sensitivity. In this model, all predicted effects of structure are determined by the value of sensitivity.

However, there are few models that can describe the mechanical behavior of structured clay in general loading conditions. Suebsuk et al. [24] proposed a generalized constitutive model for structured clay. The measurement of structure and destructuration can be described by change in the modified effective stress, which is the sum of the current mean effective stresses and additional mean effective stress. In this model, the critical state strength M varies with the Lode angle θ in three-dimensional stress space. In order to combine three-dimensional criterion (SMP· criterion) to the structured UH model, Zhu and Yao.

* Corresponding author.
E-mail addresses: zs.sjtu@outlook.com (S. Zhang), ygl@sjtu.edu.cn (G. Ye), billaday@sjtu.edu.cn (C. Liao), wjh417@sjtu.edu.cn (J. Wang).

https://doi.org/10.1016/j.apor.2018.04.011
Received 6 December 2017; Received in revised form 22 April 2018; Accepted 23 April 2018

[18] introduced the transformed stress tensor $\tilde{\sigma}_{ij}$ in the structured UH model. It should be noted that the existing generalized models only consider strength as dependent on the loading conditions.

In reality, actual triaxial tests show that the deformation of soils is also influenced by intermediate principal stress. Kumruzzaman and Yin [25] performed drained true triaxial tests on completely decomposed granite soil with a constant mean effective stress. The volumetric compression decreases with increases in intermediate principal stress. Ye et al. [26,27] investigated the influence of intermediate principal stress on normally consolidated (NC) and over consolidated (OC) clay during drained true triaxial tests. For both NC and OC clay specimens, the dilatancy decreased considerably as the intermediate principal stress increased. Prashant and Penumadu [28,29] performed strain-controlled undrained true triaxial tests on NC and OC kaolin clay. Test results for both clays showed that the peak excess pore pressure increases as the b-value $[b = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)]$ increases. Different volume changes in the surrounding clay might cause different forces to act on geotechnical engineering structures. Therefore, it is necessary to consider the effect of intermediate principal stress on the deformation of clay.

The main purpose of this paper is to investigate the behavior of structured clay under three-dimensional loading conditions and to demonstrate that a simplified superloading surface model is capable of describing the behavior of structured clay under general loading conditions. Specifically, the effect of intermediate principal stress on the strength and deformation of structured clay should be described simultaneously by the proposed model. Experimental data from undrained triaxial and drained true triaxial tests on Shanghai marine clay are presented to support the proposed model.

2. Drained true triaxial tests on structured and remolded Shanghai marine clay

The true triaxial apparatus used in the tests was recently developed by Ye et al. [26]. It applies three independent loads on cubical soil specimens using a mixed rigid-flexible boundary. For the present study, tests were performed on two separate sets of samples. The first set of undisturbed structured clay samples were taken at depths of 10 m, and were part of the 4th-layer stratum that occurs in Shanghai City. The 4th-layer stratum is a typical marine clay [30], and its physical properties are presented in Table 1. The second set of samples were reconstituted at an in-situ stress state in the laboratory. Disturbed portions of the block samples were mixed with a de-aired distilled water content of about twice the liquid limit, then reconstituted under a one-dimensional effective stress of 98 kPa.

A series of drained tests on structured and remolded Shanghai marine clay specimens were carried out under drained conditions with different Lode angles (0°, 15°, 30°, 45°, and 60°). The tests were conducted with a constant effective mean stress of 98 kPa. The mean effective stress is kept constant so that the effect of deviatoric stress on the shear strength and volume change can be obtained. Figs. 1 and 2 show the influence of intermediate principal stress (σ_2) on the shear behavior of structured and remolded clay. For both structured and remolded clay specimens, the strength and volumetric strain decrease considerably as the Lode angle changes from 0° to 60°. This behavior demonstrates that it is necessary to consider the effect of intermediate principal stress on the strength and deformation of structured clay simultaneously.

3. Model description

3.1. Transformed stress space and transformed stress tensors

The Cam-Clay model [31] with an extended von Mises failure criterion ignores the influence of intermediate principal stress and overestimates the shear strength of soil in general stress conditions other than triaxial compression conditions. To capture the shear strength of soil in general stress conditions more realistically, Yao and Sun [32,33] revised the Cam-Clay model by incorporating the critical state concept with the SMP failure criterion [34] (Mastsuoka and Nakai). As shown in Fig. 3, the SMP criterion envelope in ordinary principal stress space is converted into a circle in the transformed principal stress space. In this paper, the following transformed stress tensor $\tilde{\sigma}_{ij}$ based on the SMP criterion is used:

$$\tilde{\sigma}_{ij} = p\delta_{ij} + \frac{q_c}{q}(\sigma_{ij} - p\delta_{ij}) \tag{1}$$

where p and q represent the mean effective stress and deviatoric stress in transformed principal stress space, respectively, δ_{ij} = Kronecker's delta, and q_c is obtained as follows:

$$q_c = \sqrt{\frac{3}{2}}\, l = \frac{2I_1}{3\sqrt{(I_1I_2 - I_3)/(I_1I_2 - 9I_3)} - 1} \tag{2}$$

where l represents the radius of the circle in Fig. 3, $I_1 = \sigma_1 + \sigma_2 + \sigma_3$, $I_2 = \sigma_{1\sigma 2} + \sigma_{2\sigma 3} + \sigma_{3\sigma 1}$, and $I_3 = \sigma_{1\sigma 2\sigma 3}$, which are the first, second, and third stress tensor invariants, respectively.

3.2. A modified stress-dilatancy equation defined in transformed stress space

The yield surface of the proposed model is defined in a transformed stress space, in which $\tilde{p}$ and $\tilde{q}$ are the transformed mean effective stress and the deviatoric stress. For the normality condition, the following relationship between plastic strain increment parameters and stress parameters is based on the transformed stress space concept:

$$\tilde{p}\, d\varepsilon_v^p + \tilde{q}\, d\varepsilon_d^p = 0 \tag{3}$$

where the directions of plastic volumetric strain $d\varepsilon_v^p$ and shear strain $d\varepsilon_d^p$ coincide with those of $\tilde{p}$ and $\tilde{q}$, respectively, because the coaxiality between the plastic strain increment and the stress increment is assumed.

Based on the Cam-Clay-type stress-dilatancy relationship, a modified stress-dilatancy equation is defined in the transformed stress space for modeling the strength and deformation of clay under three-dimensional loading conditions. The relationship of the stress ratio and plastic strain increment ratio is given in the following form:

$$\frac{d\varepsilon_v^p}{d\varepsilon_d^p} = \frac{M^\beta - \tilde{\eta}^\beta}{\tilde{\eta}^{\beta-1}} \tag{4}$$

where is the stress ratio based on transformed stress space concept and M is the stress ratio in the critical state. The stress-dilatancy relationship in Eq. (4) is similar to the stress-dilatancy equation of the original ($\beta = 1$) and modified ($\beta = 2$) Cam-Clay models, though the stress increment quantities are slightly different. In order to describe the stress-path dependency of volumetric strain, the value of β is obtained using the following equation:

Table 1
Physical properties of Shanghai marine clay (4th layer).

Parameter	Density (g/cm^3)	Sand (%)	Silt (%)	Clay (%)	Liquid limit W_L (%)	Plastic limit W_P (%)	Plastic index I_P (%)	Liquidity index I_L (%)
Value	2.678	0	55.4	44.6	43.7	23.4	20.3	1.33