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A new bounding-surface plasticity model for cyclic behaviors of saturated clay

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ABSTRACT

A new combined isotropic–kinematic hardening rule is proposed based on the concept of the generalized homological center and the generalization of Masing's rule. The key point of the new hardening rule is that the unloading event can be treated as if it were virgin loading through taking the stress reversal point as the new generalized homological center of the bounding surface. Therefore, a new simple bounding-surface plasticity model with three important features for the cyclic behaviors of saturated clay is developed. Firstly, according to the movement of the generalized homological center, the model can harden not only isotropically but also kinematically to account for the anisotropy and memory the particular loading events. Secondly, the continuous cyclic loading is divided into the first loading, unloading and reloading processes and they are treated differently when calculating the hardening modulus to describe the soil responses accurately. The third feature is taking the generalized homological center as the mapping origin in the mapping rule to reflect the plastic flow in the unloading event. The behaviors of saturated clay for the monotonic and cyclic stress-controlled and strain-controlled triaxial tests are simulated by the model. The prediction results show an encouraging agreement with the experimental data.

1. Introduction

Offshore foundations, such as piles, suction anchors, bucket foundations and drag anchors, are often partially or completely embedded in seabed soils. The performance of such embedded foundations is strongly dependent upon the response of the surrounding soils, due to that under cyclic loads caused by waves and currents, significant changes can happen both in the stiffness and shear strength of soils [1–5]. The cyclic effects should be taken into account in the stability analysis of offshore foundations [6,7]. Hence, it is essential to develop more reliable and accurate soil models under long-term cyclic loading to effectively and precisely evaluate the response of embedded offshore foundations in a complicated ocean environment.

The observed typical response of a real soil undergoing cyclic loading is shown in Fig. 1 [8]. In Fig. 1, upon unloading both elastic and plastic deformations occur before the stress path is fully reversed, and cyclic loading can lead to a substantial accumulation in plastic deformation and pore pressure together with even a sudden loss in the shear strength and stiffness of the soil. Moreover, a natural deposited clay tends to be anisotropic because of the nature of its particles and environmental conditions, even the isotropic soils may present anisotropic.

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Over the last decades, there have been two remarkable types of plasticity models for cyclic behaviors of soils and other materials. One is the multi-surface model, which is based on the kinematic hardening plasticity theory [9,10], and the other is the bounding-surface plasticity theory, including the two-surface model which defines an outer surface termed as a bounding surface in addition to the inner surface or loading surface [11] and the single-surface model in which the elastic domain is reduced to a point within the consolidation or bounding surface [12–14]. Based on the two theories, many new models have been proposed and some successful results have been achieved. Mroz et al. [15] proposed a nesting yielding surface model, in which an infinite number of nesting yield surfaces within the consolidation surface translate in crowds, and they also harden isotropically during reverse loading. Li and Meissner [16] proposed a two-surface plasticity model based on a new kind of kinematic hardening rule, in which a new memory center is introduced to take into account the memory of the particular loading history, and meanwhile the memory center is considered as the mapping origin to predict the reversal plastic flow. Similarly, Khalili et al. [17] proposed a two-surface plasticity model for cyclic loading of granular soils, in which three surfaces are implied and the stress reversal point is taken as the homological center of the loading surface in order to reflect the loading history. However, because of their complicated hardening rules, which need to account for the evolution of more than two surfaces, it is difficult to be implemented in a numerical simulation or to solve a boundary value problem especially the ones referring long-term cyclic loading.

Among the above plasticity models, the bounding-surface plasticity model with vanishing elastic region has particularly attracted a great deal of interest due to its simplicity and ease of use. However, the conventional models [12–14,18,19] are usually based on assumptions that the bounding surface hardens isotropically along the hydrostatic pressure axis and the unloading response is elastic. So they are failed to predict the real cyclic responses of soils such as anisotropy and reverse plastic flow. By introducing the fabric tensor or a new rotational hardening rule, which consists of both the deviatoric and volumetric components, the single bounding-surface model can be applied to predict the material anisotropy [20,21]. However, a great number of additional parameters should be introduced into and this increases complexities of the model. Moreover, some of important features of soils subjected to cyclic loading still cannot be predicted satisfactorily by these single bounding-surface models.

The aim of the present study is to present a new simple combined isotropic–kinematic hardening rule and to develop a simple but accurate bounding-surface plasticity model for saturated clay subjected to cyclic loading. A new mapping rule is established by taking the generalized homological center as a new mapping center. The applicability and veracity of the bounding-surface plasticity model are demonstrated by comparing with the test results of saturated clay from the literature.

2. The single bounding-surface model based on a new combined isotropic–kinematic hardening rule

For a monotonic loading process, the isotropic hardening plasticity model can be successfully applied in solving boundary value problems. However, for cyclic loading processes, the classical bounding-surface models based on the isotropic hardening rule are not appropriate for modeling soil behaviors due to the following reasons [22]:

a. Soil exhibits the material anisotropy (analogous to the Bauschinger effect in metals).

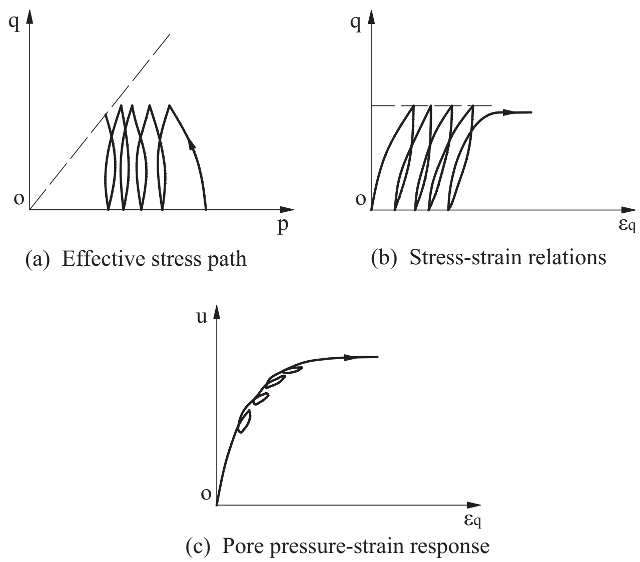

Fig. 1. Typical response observed in cyclic loading of clay.