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Incremental elastoplastic FEM for simulating the deformation process of suction caissons subjected to cyclic loads in soft clays

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ABSTRACT

This paper presents an incremental elastoplastic finite element method (FEM) to simulate the undrained deformation process of suction caisson foundations subjected to cyclic loads in soft clays. The method is developed by encoding the total-stress-based bounding surface model proposed by the authors in the ABAQUS software package. According to the model characteristics, elastoplastic stress states associated with the incremental strains of each iteration are determined using the sub-incremental explicit Euler algorithm, and the state parameters describing the cyclic accumulative rates of strains are updated by setting state variables during the calculations. The radial fallback method is also proposed to modify the stress states outside the bounding surface to the surface during determination of the elastoplastic stress states. The stress reversals of soil elements are judged by the angle between the incremental deviatoric stress and the exterior normal vector at the image stress point on the bounding surface to update the mapping centre and state variables during cyclic loading. To assess the general validity of the method, the reduced scale model tests and centrifuge tests of suction caissons subjected to cyclic loads are simulated using the method. Predictions are in relative good agreement with test results. Compared with the limit equilibrium and quasi-static methods, the method can not only determine the cyclic bearing capacity, but can also analyse the deformation process and the failure mechanisms of suction caisson under cyclic loads in soft clays.

1. Introduction

Many offshore foundations, such as deep-water suction caissons, vertically loaded anchors (VLA) and large-diameter bucket foundations, are subjected to working loads (static loads) from superstructures as well as cyclic loads from waves. Evaluating the stability of offshore foundations with cyclic loads is very important for designing offshore foundations. This evaluation includes the deformation process and the ultimate bearing capacity of foundations subjected to static and cyclic loads. More attention has been focused on the ultimate bearing capacity in previous research because it is difficult to analyse the deformation process. In general, the ultimate bearing capacity was determined using the limit equilibrium method or the pseudo-static method [1–5], however, these methods cannot be used to analyse the foundations deformation process. If the deformation process of offshore foundations subjected to static and cyclic loads is properly analysed, the failure mechanisms of the foundations can be well understood and the design capabilities of offshore foundations can be improved.

This paper presents an incremental elastoplastic finite element method (FEM) to analyse the deformation process of suction caisson foundations subjected to static and cyclic loads in soft clays. Using this approach, the cyclic and cyclic accumulative deformation time histories of the foundation can be tracked, and the failure mode of the foundation can be clearly evaluated. Meanwhile, the cyclic bearing capacity can be determined based on the appropriate failure criterion of displacement. Compared with the limit equilibrium analysis method, the proposed method is more applicable to three-dimensional problems with complicated boundary conditions.

The key issue in analysing the deformation process of offshore foundations in soft clays using the incremental elastoplastic FEM is the use of a constitutive model that describes the cyclic stress-strain responses of soft clays. Two types of constitutive models are commonly used: the effective stress-based constitutive model [6–13] and the total stress-based constitutive model [14–17]. Many researches have been performed to calculate the deformation of clays using the effective stress-based model. Li and Meissne [18]

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and Hu et al. [19] separately developed an effective stress-based two surface model and a bounding surface model and analysed the cyclic responses of a strip foundation by using two-dimensional finite element calculations based on the models. Certain studies (Ibsen et al. [20] and Bourgeois et al. [21]) developed effective stress-based multi-surface and single-surface models to analyse the deformation process of the single pile in clays using models based on three-dimensional finite element calculations. Fan et al. [22] applied the improved Cambridge dynamic constitutive model developed by Carter et al. [23] to the incremental elasto-plastic finite element calculations and analysed the deformation processes of bucket foundations in soft clays and subsequently discussed the failure mechanism of foundations subjected to cyclic loads and the distribution of excess pore pressure in soft ground. Because the effective stress-based constitutive model generally includes the complex interpolation function of the plastic modulus and the hardening rule with many parameters, many models can only be applied to the analysis of two-dimensional boundary value problems [18,19,22]. A widely applicable analytical method for three-dimensional problems with complicated boundary conditions and loading conditions is still not available.

Thus far, research on calculation of the deformation of soft clays subjected to static and cyclic loads using total stress-based constitutive models is relatively scarce. Anastasopoulos et al. [16] and Huang et al. [17] analysed the cyclic responses of shallow foundations and pile foundations in soft clays using the FEM based on a total stress model, respectively. When using total stress-based models, the hardening modulus field is generally constructed in the deviatoric stress space and the incremental deviatoric stress-strain relationship is built. Because the total stress-based model involves only the hardening mechanism of plastic deviatoric strain, the expression of the hardening modulus is relatively simple and relatively less model parameters are needed. The implementation of 3D finite-element calculations is easier for the total stress-based model as well.

Because the suction caisson in soft seabed clays is operated immediately after installation and soft clays have very low permeability, the soft clays surrounding the suction caisson are undrained when subjected to static and cyclic loads [24]. The deformation of suction caissons results from the deviatoric deformation of soft clays subjected to static and cyclic loads. Therefore, it is appropriate that the deformation process of suction anchors is analysed using total stress-based constitutive models.

The authors developed a total stress-based incremental elasto-plastic bounding surface model that describes the undrained stress-strain responses of soft clays subjected to static and cyclic loads. The mathematical expression of the model is relatively simple, the number of model parameters are less and the parameters are determined using regular cyclic triaxial tests under undrained conditions [25]. In this paper, the model is encoded in ABAQUS through the subroutine UMAT. The incremental elasto-plastic FEM used to analyse the deformation process of suction caissons subjected to static and cyclic loads was developed using the incremental solver in the ABAQUS software package. The deformation processes of suction caissons subjected to static and cyclic loads were analysed using the method based on the model test conditions, and the calculation results were compared with the model test results to verify the feasibility of the method.

2. Constitutive model

The constitutive model was described in detail in a previous paper by the authors [25]. Because this paper focuses on the numerical implementation of the constitutive model, the model is briefly introduced to understand the incremental elastoplastic analysis method developed in the paper.

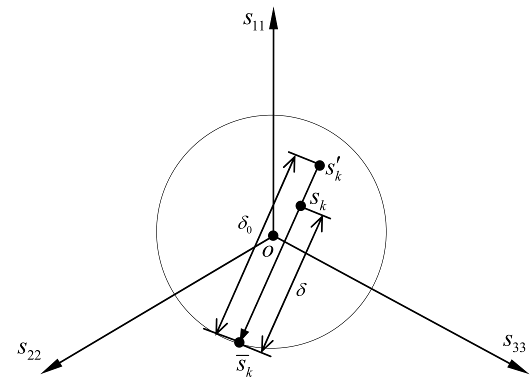

Fig. 1. Mapping rule for loading and unloading.

2.1. Basic equations

Because the yielding and failure of soft clays depend only on the deviatoric stress under undrained conditions [14,26,27], the failure and the evaluation of the hardening modulus are described in the deviatoric stress space. The model includes three basic equations: the bounding surface equation describing the failure of the soil element, the relationship describing the evolution of the hardening modulus in the deviatoric stress space and the incremental elastoplastic deviatoric stress-strain relationship.

The bounding surface equation is described using the Von Mises function, as shown in Eq. (1).

$$F = \frac{3}{2}\bar{s}_{ij}\bar{s}_{ij} - A_0^2 = 0 \tag{1}$$

where $\bar{s}_{ij}$ denotes the deviatoric stress tensor of the bounding surface, and A_0 denotes the radius of the bounding surface.

The evolution of the elastoplastic hardening modulus is described using Eq. (2). The mapping rule is schematically shown in Fig. 1 for loading and unloading, and s_k', s_k and $\bar{s}_k$ denote the mapping centre point, the current stress point and the image stress point, respectively. The image stress point is defined as the intersection point of the bounding surface and a line passing through the mapping centre point and the current stress point. The initial loading point is the mapping centre during initial loading. For unloading and reloading after stress reversal, the mapping centre is defined as the stress reversal point.

$$H = \left(\frac{\delta}{\delta_0}\right)^{\mu} H_{\max} \tag{2}$$

where H denotes the elastoplastic modulus of the current stress point, δ is the distance between the current stress point and the image stress point, δ_0 is the distance between the mapping centre and the image stress point, $H_{\max}$ represents the maximum elastoplastic modulus and μ is the undetermined relationship expressed in Eq. (3) and reflects the accumulative rate and the level of accumulative shear strain.

$$\mu = \mu_0 d\gamma_{8,p} \tag{3}$$

where $d\gamma_{8,p}$ denotes the octahedral cyclic accumulative shear strain increment after each stress cycle, depends on the stress history and current cyclic stress level and controls the trends of the accumulative shear strain versus the number of stress cycles, and the coefficient μ_0 controls the level of the accumulative shear strain after a certain number of stress cycles.

The plastic deviatoric strain increment is obtained according to the associative flow rule and Eq. (1). In addition, the elastic deviatoric strain increment is obtained according to the generalised Hooke's law. Thus, the elastoplastic deviatoric stress-strain rela-