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Research Paper

Multi-directional modeling for prediction of fabric anisotropy in sand liquefaction

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ABSTRACT

Anisotropy in the onset of liquefaction and post liquefaction under cyclic loading condition causes the change in response behavior of the soil. The proposed model operates within the integration of sliding/opening/closing framework of 17 predefined planes as local deformation. This leads to the use of better stress/strain multilaminate histories with many directional effects on soil behavior specifically internal mechanism during pre and post-liquefaction. The ability of multilaminate model for fabric anisotropy has been proven by comparison with the experimental results under drain and undrained conditions and monotonic and cyclic loading. The effects of induced anisotropy was also investigated.

1. Introduction

During its lifespan, sand is sedimented and forms under different environmental conditions. The bedding plane will, thus, cause formation of strong and weak planes in different directions. This initial anisotropy causes different behaviors in the sand under different loading conditions. Another type of anisotropy develops in granular materials in response to the loading and generation of plastic strains in various directions. This type of anisotropy is known as induced anisotropy and brings about important effects in the behavior of sandy soil under different conditions. The three important characteristics of granular soils are liquefaction, dilatancy and limit state conditions, which develop during loading and are influenced by induced anisotropy. Movement direction of the grains of soil after the onset of liquefaction (post-liquefaction), is also caused by the effect of initial and induced anisotropy.

The anisotropic effects of fabric have been investigated through a series of experimental studies on the response of sandy soil [1–3]. In this research, the history of soil sediment in anisotropy creation and its effect on soil behavior response under static and dynamic condition are noted.

Some have also attempted to model the important characteristics of sand, such as the state of transition, liquefaction and limit state, by developing a relation between its macroscopic and microscopic structure [2,4–14]. Other studies have attempted to predict the anisotropic behavior of fabric using different parameters and introducing them into soil constitutive law [1,4,15–19]. A few studies have taken the effects of induced anisotropy into account using constitutive laws [20–22].

Despite the existence of different models for predicting the behavior of sandy soil under different loading conditions [4,16,17,23–26], they have been employed under limited conditions of anisotropy or loading or by using a large number of material constants .

The multilaminate behavior model, also known as the microplane model [27,28], considers material behavior on different planes and is a suitable mechanism for simultaneous prediction of complete anisotropy in sandy soil. This model can play an important role in predicting the behavior of granular soils owing to basic changes in calculation methodology and the use of multiple planes instead of three planes Cartesian coordinate system. This model has been evaluated for soil [29–31] as well as for estimation of damage models in concrete [32,33]. Some researchers have considered 13 planes in different directions of a sphere with a radius of one to model the effects of behavioral anisotropy using different models in planes [30,31,33]. In these recent models, the consideration of 13 planes providing simultaneous consistency of strains and equilibrium encountered problems [32,33].

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The current study uses multilaminate theory and 17 planes defined in different directions with specific weight coefficients and directions, after which the effects of the 17 planes are transferred to one point within the framework of numerical integration method. This model considered 17 planes with pre-defined directions instead of defining all the events associated with direction on three orthogonal Cartesian coordinate systems using numerical integration. Accordingly, the anisotropy in the behavior of matter is evaluated on 17 planes with more accuracy and power, instead of three orthogonal planes. The proposed model can predict anisotropy of any degree of complexity and distribution in different directions and involves the effects of any boundary conditions with retained directional effects in the behavior of total matter. The projections of rotation of the principal axis and lack of coaxiality of stress and strain are among distinguishing features of multilaminate model.

In this paper, to model the behavior in the planes, an advanced numerical model is modified by reducing the soil constants based on limit state and hypo-plasticity theory [34–36] and is able to predict the behavior of sand under drained and undrained conditions with monotonic and cyclic loading. Within the framework of the multilaminate method, the equations governing the plane are briefly introduced and the constants of the model are obtained in the planes with calibration. Thereafter, the ability of the model under different loading states, confining pressures and void ratios is compared with triaxial standard test results and verified. Next, induced anisotropy is investigated in the 17 planes under different conditions. The effects of induced anisotropy are demonstrated by the curves of the stress and strain paths and stress–strain in the planes. The active and inactive and leading planes in failure are specified in the triaxial standard test and the ability of the model to predict the behavior in different directions is investigated.

2. Multilaminate model

The basis of multilaminate theory [37] is the determination of the numerical relationship between inter-particular behavior (microscopic behavior) and engineering mechanical properties (macroscopic behavior) in the form of a constitutive equation. The properties of the material are obtained from each of its constituent elements and achievement of the stress–strain behavior of the material is made possible by investigating the inter-particular behavior. When a multidimensional piece undergoes the effect of small shear stress, it experiences elastic shear deformation. As the stress increases and reaches a certain value, the multidimensional pieces begin to move along the boundary planes, which are called sliding planes. As the deformation increases, the required shear stress which develops further deformation also increases. The total shear deformation at any time is the total elastic shear deformation in the multidimensional pieces in addition to the plastic shear deformation caused by the sliding of adjacent pieces. As the stress decreases, the elastic component returns to the beginning of the path. After that, a further decrease in stress (unloading) occurs and, as it reaches a certain value, the multidimensional pieces begin to slide along the inverse direction. The shear stress required for development of sliding is dependent on the vertical stress, for which sliding occurs only when the stress state exceeds the yield surface limit. Furthermore, sliding takes place only in planes having the directions shown in Fig. 1. Accordingly, the greater the number of predefined planes, the closer to reality will be the sliding and opening-closing of the planes.

In multilaminate theory, the numerical integral is a specific mathematical function developed over a sphere surface having a radius of one. This mathematical function can express changes in physical properties over the surface of the sphere. On the surface of this hypothetical sphere, numerical integration can be estimated using an unlimited number of flat planes which are tangential to specific points on the surface of the sphere (Fig. 2). In this way, each plane has a contact point with the surface of the sphere. Limiting the number of such planes will define the number of contact points (reference points). When calculating the numerical integral, it is possible to obtain the quantity through development over the sphere surface at the reference points. The numerical integral for the continuous function of $f(x,y,z)$ on the surface of a sphere is the sum of $f(x,y,z)$ at the sample points multiplied by weight coefficients related to these points. The number of sample points should be increased to decrease the error. The following relationship represents the relation between numerical and typical integral:

$$\iint_{\Omega} f(x,y,z)dxdydz = 4\pi\sum_{i=1}^{n} w_{(i)} f_i(x_i,y_i,z_i) \tag{1}$$

Ω = area of sphere
n = number of points
$w_{(i)}$ = weight coefficient of point i
$f_i(x_i,y_i,z_i)$ = value of function f at point i.

If the manner of sliding and the opening-closing of each plane is regulated, the sum of these can be used to construct the internal mechanism of the material movement for one point. Through integral summation, the overall effects of the movement or deformation at one point can be obtained.

To better represent the geometry of the planes in the model, the tangential planes equivalent to these micro-planes are used on the hemisphere. Fig. 2 shows their place on sphere and inside the unit cube. Table 1 lists the directional cosines, the directions of shear stress τ_{n_1} and τ_{n_2} and the weight coefficients of the 17 planes.

If l, m, and n are the directional cosines of the perpendicular to the plane, then l', m', and n' are the directional cosines of the shear stress τ_{n_1} and l'', m'', and n'' are the directional cosines of the shear

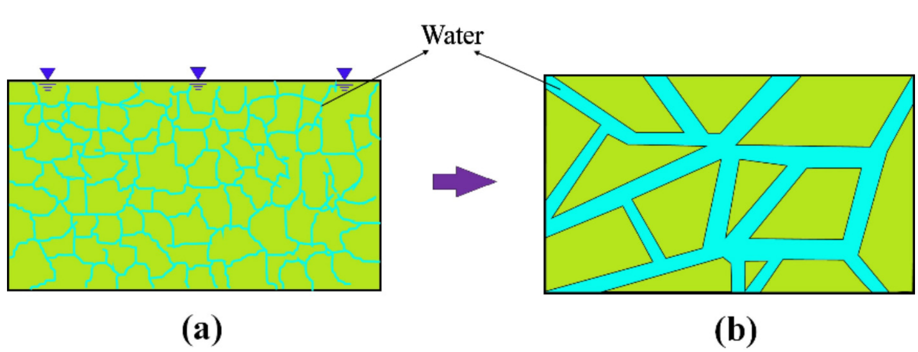

Fig. 1. (a) Real aggregation of particles; (b) 2D representation of aggregation of artificial multidimensional pieces.