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Fabric assessment of damaged anisotropic geo-materials using the multi-laminate model

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ABSTRACT

Fabric or texture of intact geo-material affects its degree of anisotropy, and results in various mechanical properties in different orientations. It is a complicated problem, and it is important to consider fabric variations under different stress paths. Applied stresses change the fabric of the material, and change its rigidity and stiffness in different directions. Classic models are developed based on the invariants of stress tensor. These invariants do not carry the characteristics of the material in different directions, and most of the directional information of the material behaviour is being missed. To overcome these issues, a simple methodology was outlined to predict the behaviour of a geo-material in various orientations due to anisotropy. Multi-Laminate model, which is capable of considering the behaviour of material in different directions, was utilized as the framework of this study. Three damage functions and three ellipsoids were used to consider degradation of the material and spatial rigidity distribution around a point, respectively. The shape of the ellipsoids might be changed during the loading history due to fabric evolution. Model results were compared with some tests results. Mechanism of failure was predicted via investigating the damage functions. Fabric evolution was assessed, and rigidity variation of material under a cyclic stress path was investigated.

1. Introduction

Generally, all particulate materials are naturally anisotropic and formed by a process of sedimentation or water/air pluviation. However, the process of sedimentation, as well as the pressure exerted by the overlaying material, causes flat particles to be oriented with their longest dimensions, approximately parallel to the plane of deposition. This condition is achieved upon the minimum energy law of nature, and causes a better interlocking of grains to the others. As a result, strength increases against applied loads in a direction perpendicular to the bedding plane. Most of the natural rocks possess transversely isotropy structures. However, anisotropy manifested itself through the directional dependence of deformation characteristics of granular materials and this has been widely documented in the literature (e.g. Oda [1] and Arthur and Menzeis[2]). Furthermore, the degree of anisotropy may vary quite significantly, depending on the soil composition, electro-chemical properties of pore water, consolidation history, etc.

Given the intrinsic oriented nature of soil or rock fabric, it is important to consider the effect of anisotropy by a logical method. The major obstacles in this way are our ability to properly define the spatial and temporal variations of the material properties, deformability, hardening/softening and boundary conditions. The value of a model depends primarily on its ability to capture the basic trends in the material behaviour, and thereby provide a more realistic representation of the problem.

However, further than the fabric property of natural sedimentary materials, the response to a given stress depends on the orientation of that stress. This nature is also observed in a random arrangement of constituent glass balls, where obviously there is no effect of fabric on the composition by Oda.[1] This characteristic is, in general, known to be due to the motion tendency of the constituent particles. This tendency can actually affect the geometry of contact points of each particle, regardless of shape and particle sizes.

The mechanical behaviour of geo-materials is often assumed to be isotropic, when the distribution and shape of particles or crystals is statistically independent of the orientation of the chosen coordinate axes. However, the mechanical laws govern their behaviour are also isotropic, and these laws can be defined independent of the used coordinate axes chosen to define the stress/strain mechanical behaviour tensors.[3] On the other hand, stress/strain invariants, used in most of the models, act as scalar values not to carry orientation information of parameters. Therefore, through the use of these parameters, the effects caused by the change of orientation properties may not to be seen in the model.

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Some investigators tried quantifying some important features of the micromechanical behaviour of granular media by introducing the average characteristics of fabric anisotropy and certain statistical averages of contact forces.[4] The stress strain relationship can be derived as an average of the mobilization behaviour of particle's local contact planes.[5] The basis of these studies is devoted to the study of anisotropic specimens loaded in different directions, which shows how the model is capable of considering the influence of inherent anisotropy on the stress-strain response under a tri-axial loading condition. Some researchers have focused on quantifying the relationships between true stress and applied stress, using discrete element simulations [6,7].

Other analyses have been carried out on the anisotropy, using pure mathematical relations and introducing fabric concept as a tensor. Geometrical state of the granular material grains is calculated in each step of loading via evolution rules defined in the model.[8] Mathematical models have some constraints and exclusions in representing the fabric state of the material, hence mechanical equilibrium conditions shall be utilized to overcome this issue; however this modification adds to the complexity of the model.

Micromechanical understanding of the response of the granular material is fundamental for understanding the macroscopic behaviour of the granular formations. In this paper, multi-laminate framework has been used as the basis of the work. Using this framework enhanced the model to consider the directional information of the material in comparison with the classical models, which use only stress invariants. Utilizing damage theory, constitutive law was written based on vectors instead of tensors, which simplifies the stress-strain relationships and helps better understanding of the concept of the model. Spatial variation of the stiffness of inherent anisotropic material was taken into account using a simple method. Three ellipsoids defined the distribution of tensile, compressive and shear rigidity on different planes. To consider the effect of stresses on fabric rotation and rigidity degradation of the material in different directions, simple rules based on experimental observations were developed and utilized. Using these techniques gave the model the capability of predicting stiffness variations of anisotropic material upon induced anisotropy and consequently fabric alterations and failure mechanisms, while keeping simplicity.

2. Multi-laminate framework

In general continuum mechanics, the components of stress or strain tensors, are defined on the surface of a cubic. This imposes some limitations to the real situation of the problem. In this approach, only three perpendicular axes of infinite number of axes are taken into consideration. Nonlinear problems depend strongly on stress strain path and their relevant histories in all directions at a point. Upon these circumstances, it may be claimed that many of the directions' information will be missed if only three directions are considered during the loading procedure.

Certainly there are infinite numbers of strain history at all orientations passing from a node. To collect and reflect all of these historical information at all orientations, a spherical element, carrying strain components over its surface, is required. Stress variations may be integrated over the sphere surface, or a numerical integration may be utilized for more simplification. Using numerical integration simulates the curved surface of the sphere to a polygon surface, approximately close to the sphere. Higher accuracy is expected at higher numbers of the polygon tangential flat planes.

For a granular mass, such as sand that supports the overall applied loads through contact friction, the overall mechanical response ideally may be described on the basis of micro-mechanical behaviour of grains or particles interconnections. Naturally, this requires the description of overall stress, characterization of fabric, representation of kinematics, development of local rate constitutive relations and evaluation of the overall differential constitutive relations in terms of the local quantities. Representation of the overall stress tensor in terms of micro level stresses and the condition, number and magnitude of contact forces has long been the aim of numerous researchers (Christofferson et al.[9] and Oda et al.[10]).

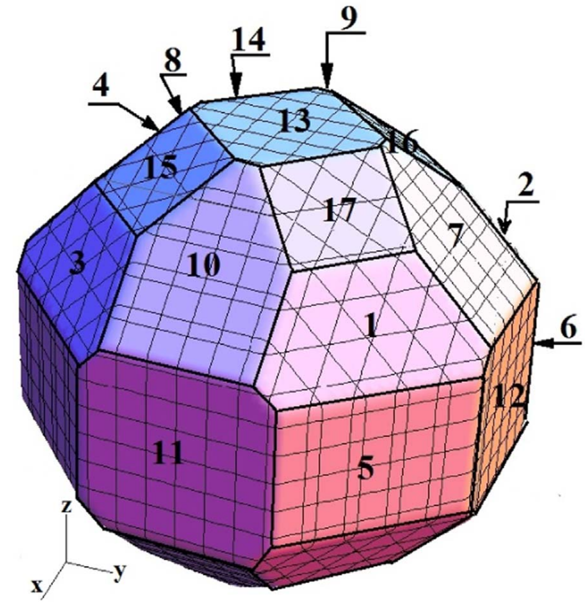

Fig. 1. Sampling planes location and polyhedron made by 34 sampling planes.

Multi-laminate framework, by defining small continuum structural units as an assemblage of particles and voids that fill infinite spaces between the sampling planes, has appropriately justified the contribution of interconnection forces in overall macro-mechanics. These assumptions adopt that overall sliding, separation or closing of inter-granular points of grains, included in one structural unit, are summed up and contributed as the result of sliding, separation/closing surrounding boundary planes.

Fig. 1 shows the arrangement of sampling planes that approximate the sphere and artificial polyhedron made by the crossing of 2×17 sampling planes. Orientation of each sampling plane is tabulated in Table 1. [11,12]

In an ideal case, the normal integration is considered the summing up of individual micro effects corresponded to the infinite number of

Table 1
Direction cosines and weight factors of sampling planes.[11,12]

Plane No.	Direction Cosine with respect to x axis	Direction Cosine with respect to y axis	Direction Cosine with respect to z axis	Weight Factor
1	$1/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$	0.020277985
2	$-1/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$	0.020277985
3	$1/\sqrt{3}$	$-1/\sqrt{3}$	$1/\sqrt{3}$	0.020277985
4	$-1/\sqrt{3}$	$-1/\sqrt{3}$	$1/\sqrt{3}$	0.020277985
5	$1/\sqrt{2}$	$1/\sqrt{2}$	0	0.058130468
6	$-1/\sqrt{2}$	$1/\sqrt{2}$	0	0.058130468
7	0	$1/\sqrt{2}$	$1/\sqrt{2}$	0.030091134
8	0	$-1/\sqrt{2}$	$1/\sqrt{2}$	0.030091134
9	$-1/\sqrt{2}$	0	$1/\sqrt{2}$	0.030091134
10	$1/\sqrt{2}$	0	$1/\sqrt{2}$	0.030091134
11	1	0	0	0.038296881
12	0	1	0	0.038296881
13	0	0	1	0.02930060
14	$-1/\sqrt{6}$	$-1/\sqrt{6}$	$\sqrt{2/3}$	0.019070616
15	$1/\sqrt{6}$	$-1/\sqrt{6}$	$\sqrt{2/3}$	0.019070616
16	$-1/\sqrt{6}$	$1/\sqrt{6}$	$\sqrt{2/3}$	0.019070616
17	$1/\sqrt{6}$	$1/\sqrt{6}$	$\sqrt{2/3}$	0.019070616