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Research Paper

Resilient properties of binary granular mixtures: A numerical investigation

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ABSTRACT

The effect of stress level on the resilient modulus for binary mixtures of elastic spheres under triaxial loading is investigated using the discrete element method. The secant modulus during the first cycle of unloading is used as an estimate of the modulus after several load cycles due to computational time restrains. Later in the paper, its adequacy as an accurate and efficient estimator is shown. Numerical results are statistically compared with existing relations characterizing the stress dependency of the resilient modulus for real granular materials. It is concluded that the modulus prediction is significantly improved considering the effect of the deviator stress in addition to the confinement stress, obtaining a good correlation between the modulus and the confinement to deviator stress ratio for the numerical mixtures. The stress dependency of a recently proposed soil fabric classification system, based on force transmission considerations at particulate level, is also studied and its correlation with performance investigated. It is found that the relative load-bearing role of coarse and fine components is governed by the deviator to confinement stress ratio. However, the implemented fabric classification is fairly insensitive to changes in this ratio. Regarding resilient performance, interactive fabrics show the stiffest response whereas underfilled fabrics should be avoided due to a potential for instability.

1. Introduction

Unbound granular materials (UGM) are widely used as construction materials in foundation works and civil engineering structures, including transport infrastructures. In Sweden, the deliveries of construction aggregates in 2013 accounted for a total of 76.4 m tonnes (equivalent to 7.9 tonnes per capita) of which 42.4 m tonnes were used for road construction according to SGU [1].

UGM layers are an integral part of the pavement structure, playing a significant role on its overall stiffness and performance. Mechanistic design frameworks for pavement structures rely on reliable material models, where the stiffness of the unbound layers is generally characterized by the resilient modulus M_r and Poisson's ratio v of the material. For repeated load triaxial testing RLTT with constant confinement, the resilient modulus is classically defined as a ratio of the applied deviator stress σ_d and the recoverable or resilient part of the axial strain $\varepsilon_{a,r}$ during unloading [2]

$$M_r = \frac{\sigma_d}{\varepsilon_{a,r}} \tag{1}$$

In standards, this relation is usually accompanied by a requirement of a certain number of load applications (few hundreds to thousands) prior to the measurement of the above parameters in order to reach a stable resilient behaviour, *i.e.* conditioning of the sample.

The unloading–reloading response of granular materials is essentially non-linearly inelastic and influenced by numerous factors, as can be seen in the extensive literature review conducted by Lekarp et al. [3]. According to the latter, stress level is shown without exception as the most significant factor. Nevertheless, there is not a consensus on how the stress level affects the resilient modulus. Several researchers have proposed different statistical models describing the stress dependency of the resilient modulus based on different stress-related variables. Table 1 summarizes some of the most commonly used models found in the literature, rewritten in a convenient form to allow for an easier comparison for the case of triaxial loading, where power functions based on different stress

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Table 1
Some commonly used models to describe the resilient modulus dependency on stress level under triaxial loading conditions.

Expression	Ref.	Eq.
$M_r = k_1\sigma_c^{k_2}$	Dunlap [4]	(2)
$M_r = k_1\sigma_c^{k_2}\sigma_d^{k_3}$	Pezo [5]	(3)
$M_r = k_1 p^{k_2}$	Seed et al. [6]	(4)
$M_r = k_1 p^{k_2}\sigma_d^{k_3}$	Uzan [7]	(5)

variables (*i.e.* confinement stress σ_c, deviator stress σ_d and mean normal stress $p = \sigma_c + \sigma_d/3$) are used and k_1, k_2 and k_3 represent regression constants unique to each function and material.

For gap-graded materials, the relative content by weight of fine particles is key in defining the soil fabric structure and its behaviour. Based on empirical observations, previous studies by Vallejo [8] and Thevanayagam et al. [9] have proposed soil fabric cases where the roles of the coarse and fine particles on different aspects of the material behaviour are inferred from the observed macroscopic response. In a more recent study, de Frias Lopez et al. [10] proposed a synthesis of the above systems to study load-bearing mechanisms of binary mixtures under triaxial loading. Following earlier numerical studies on force transmission by Minh et al. [11], the proposed system defines fabric cases by means of explicitly quantifying the relative contribution to resist the applied deviator stress of the different interparticle contact-type networks within the soil, *i.e.* coarse-to-coarse (*c*–*c*), coarse-to-fine (*c*–*f*) and fine-to-fine (*f*–*f*). Fig. 1 summarizes the proposed system, where:

Case A: Coarse grain supported fabric structure with none or very small amount of fines *underfilling* the voids between the coarse grains with low contribution to the load-bearing skeleton. The *c*–*c* contact network forms the main load-bearing skeleton.
Case A-1: Special subcase of fabric A where, due to the relatively low content of fine particles, single fine grains become trapped between coarse particles aligned along the applied deviator stress direction creating a potential for instability. Reduced performance is expected for such materials.
Case B: Transitional coarse grain supported structure where the main contributor is the *c*–*f* network, indicating a strong interaction between coarse and fine particles. The coarse grains are still responsible for the main load-bearing skeleton, whereas the fines remain generally confined within the voids between the coarse particles providing a significant support to its skeleton, together with some possible local disruption to its contact network. Improved performance can be expected within this fabric.
Case C: Transitional fine grain supported structure where the *c*–*f* network remains as main contributor, but the *f*–*f* network provides a higher contribution than the *c*–*c*. This case represents the turning point where the fines have started *overfilling* the voids between the coarse particles, extensively disrupting its contact network and generating a new fine particles skeleton which receives a significant reinforcement by the coarse particles network.
Case D: Fine grain supported structure with none or very few coarse grains floating in a matrix of fines and which may provide a small reinforcement effect on its skeleton. The main contributor is the *f*–*f* network, with a low to insignificant contribution by the *c*–*c* contacts.

Fields of engineering dealing with granular materials, like soil mechanics or pavement and railway engineering, have traditionally heavily relied on statistical models based on empirical results, partly due to the discrete nature of the problem concerning the fundamental constitutive relations of granular materials. In this regard, the discrete element method DEM, firstly proposed by Cundall [12] for the analysis of rock-mechanics problems and later applied to soils by Cundall and Strack [13], presents an alternative to continuum based computer models like the finite element method to study the behaviour of discrete systems at macroscopic level with explicit consideration of internal processes at particulate level. At present, one of the main limitations regarding the use of DEM is computational time when a large number of particles are involved; in particular, for the case of modelling cyclic triaxial tests on granular materials, it is obvious that this limitation becomes more restrictive with the number of loading cycles to be simulated, making it unrealistic to perform simulations with large number of cycles.

In the present study, DEM is used to study the effect of stress level on the resilient modulus of idealized gap-graded granular materials, *i.e.* perfect binary mixtures of elastic spheres, under triaxial loading. As a first step, the secant stiffness resulting from dividing the maximum applied deviatoric stress by the recoverable part of the axial strain during first unloading is used as an estimate of the long term resilient modulus to reduce computational time. Later in the paper, the adequacy of the proposed estimator is examined. Numerical test results on cylindrical specimens are compared with current knowledge obtained from empirical studies on granular materials (*cf.* Table 1) in order to identify the main stress variables influencing the material performance. Additionally, the stress dependency of the presented soil fabric classification system (*cf.* Fig. 1) is analysed and the possible statistical significance of the fabric structure on material performance is investigated.

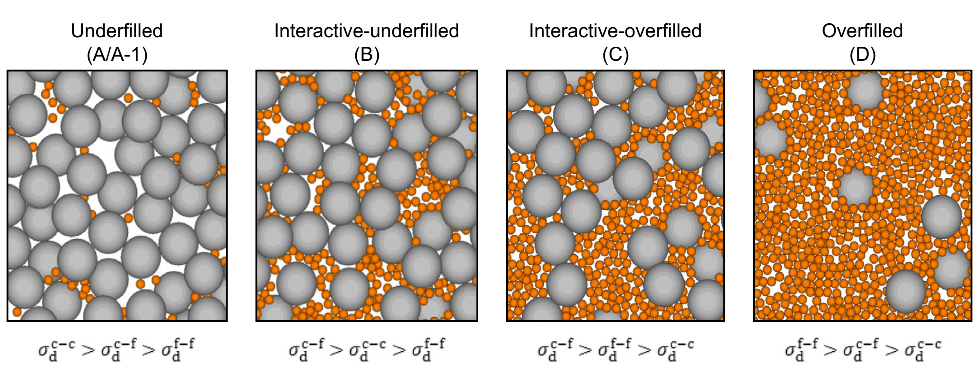

Fig. 1. Soil fabric classification system for the study of load-bearing mechanisms of coarse–fine granular mixtures after de Frias Lopez et al. [10].