Shear Modulus Degradation and Its Association with Internal Damage in Cemented Granular Material

Zhifu Shen[1(✉)], Mingjing Jiang[2], Zhihua Wang[1], and Shengnian Wang[1]

[1] Institute of Geotechnical Engineering, Nanjing Tech University, Nanjing 210009, China
zhifu.shen@njtech.edu.cn

[2] Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

Abstract. Cemented granular material is featured by the presence of interparticle bonds. In mechanical loading, bond breakage results in a transition from an intact state to a fully disturbed state. However, it is impossible to directly track and measure the breakage of each individual bond among the millions of bonds in a small sample. This study applied discrete element method simulation to associate the evolution of a micro-scale-based damage variable with the degradation of measurable shear modulus in cemented sand. The simulations show that bond breakage is highly non-uniform in a sample. As a result, the sample is deteriorated by the detachment of particles from the main skeleton and the detached particles are found to take no load in the initial stage. This explains the observed sharp degradation of shear modulus. With further bond breakage, the skeleton is disassembled into assembly of particle-clusters, but the shear modulus only varies slightly. The implication for establishment of a physically robust constitutive model for cemented sand is discussed.

Keywords: Cemented sand · Structural damage · Shear modulus degradation

1 Introduction

Cemented granular materials are common in geotechnical field, e.g. cemented sand [1], gas hydrate bearing sediment [2] and weak rock [3]. Constantly increasing knowledge in micro-structure facilitates the development of constitutive model with consideration of particle-scale mechanism [4]. However, the lack of understanding in the association of microscopic quantities and macroscopic measurable quantities hinders reliable determination of some model parameters that has been embedded with microscopic meaning. This study focuses on the association of particle-scale bond breakage and degradation of macroscopic shear modulus.

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2 DEM Simulation of Cemented Sand

Cemented sand was idealized as an assembly of bonded spheres in this study. The bonding material is assumed to sparsely distribute at distinct contacts. The bond contact model, particle size distribution and the basic set of contact model parameters in [5] were used. Cubic samples with 40,000 spherical particles were simulated. Four samples were modelled to study the effects of sample density and bond content: S1 (initial void ratio $e_0 = 0.80$, bond content $c = 1.0\%$ which was defined as the ratio of total bond material volume over total particle volume), S2 ($e_0 = 0.80$, $c = 3.0\%$), S3 ($e_0 = 0.92$, $c = 1.0\%$), and S4 ($e_0 = 0.92$, $c = 3.0\%$). Constant-p triaxial shear tests were simulated with $p = 400$ kPa.

Figure 1 shows that increase in sample density (decrease in void ratio) and bond content can increase the peak strength and dilation. The softening behavior of sample S3 is accompanied with contraction, which is a feature of loose weakly-cemented soil.

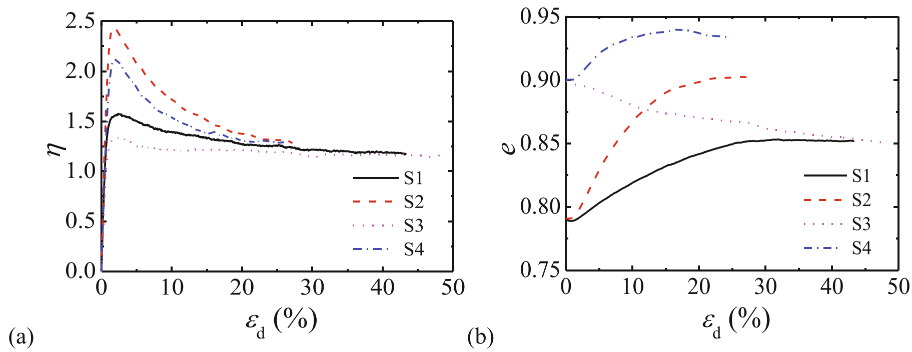

Fig. 1. Effects of sample density and bond content on mechanical behavior ($\eta = q/p$, ε_d = deviator strain): (a) stress ratio versus deviator strain, (b) void ratio versus deviator strain.

3 Bond Breakage and Shear Modulus Degradation

A damage variable θ is defined as the fraction of unbonded contacts in an assembly to describe the degree of bond breakage. Shear modulus G was measured at various points along the constant-p loading path by applying one unloading-loading loop with a variation in deviator strain of 0.2%. The loop is realized by reversing the velocity of the loading plate perpendicular to the major principal stress direction. The shear modulus was determined from the average slope of the unloading-loading path in the deviator strain- deviator stress plot. Figure 2 presents the degradation of shear modulus (normalized by the initial value G_0) with the development of bond breakage. Figure 2 shows that the shear modulus drops sharply when θ is less than 0.1, which is followed by a much slower degradation to a minimum around $\theta = 0.2$. After that, little variation in shear modulus is observed. The degradation of shear modulus keeps sound pace with the decrease in coordinate number Z as shown in Fig. 2.

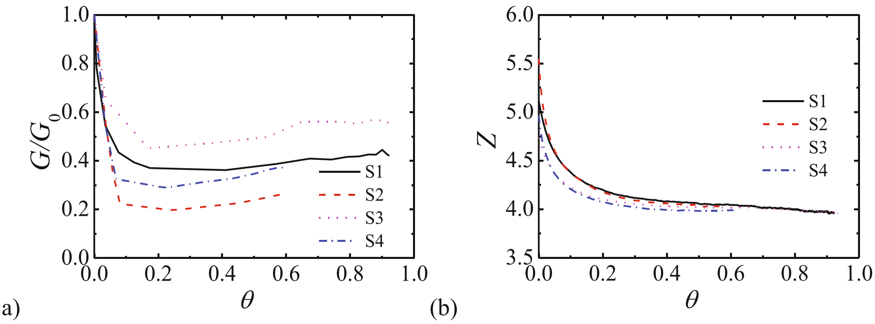

Fig. 2. Degradation of shear modulus: (a) degradation of shear modulus, (b) evolution of coordinate number.

The microscopic structure change is examined here to explain the numerically observed nonlinear degradation of shear modulus with bond breakage. Our DEM simulation results show that the heterogeneous nature of granular material leads to spatially non-uniform bond breakage events. This allows the formation of bonded particle clusters, which are groups of particles connected through bonded contacts. The presence of clusters had been confirmed in experiments [6]. With the aid of DEM simulation, Fig. 3 visualizes the spatial configuration of particle clusters, which are distinguished by colors (see the online version of this paper). The initial intact cemented assembly can be viewed as a particle skeleton. Bond breakage mainly leads to detachment of small clusters (usually consisting of several particles) from the skeleton when θ is less than 0.2. The skeleton bears external load and it is gradually deteriorated due to the detachment of particles. With further bond breakage, the skeleton is disassembled into assembly of particle-clusters. To quantitatively examine this feature, the average stress σ_{ij} of a granular assembly is expressed as

$$\sigma_{ij} = \frac{1}{V}\sum_{k=1}^{N_p}\sum_{m=1}^{N_{c,k}} f_j l_i = \underbrace{\frac{1}{V}\sum_{k=1}^{N_s}\sum_{m=1}^{N_{c,k}} f_j l_i}_{\sigma_{ij,s}} + \underbrace{\frac{1}{V}\sum_{k=1}^{N_p-N_s}\sum_{m=1}^{N_{c,k}} f_j l_i}_{\sigma_{ij,d}} = \sigma_{ij,s} + \sigma_{ij,d} \quad (1)$$

where V is the sample volume, f_j is the contact force, l_i is a vector pointing from particle centroid to contact center, N_p is total particle number, N_s is particle number in the skeleton and $N_{c,k}$ is the number of contacts around particle k. The stress can be partitioned into skeleton stress ($\sigma_{ij,s}$) and detached particle stress ($\sigma_{ij,d}$), respectively.

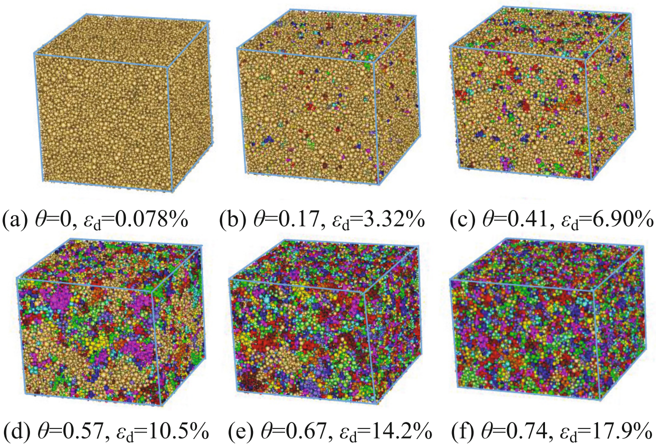

Fig. 3. Spatial configurations of particle clusters

Figure 4 presents the contribution of detached particles to the overall stress. When θ is less than 0.2, the very little contribution of $\sigma_{ij,d}$ (less than 1.0%) suggests that detached particles actually float in the skeleton voids. That is, the detached particles take no load and act as voids in the sample. The degradation in shear modulus therefore is a result of the deterioration of the initially intact skeleton.

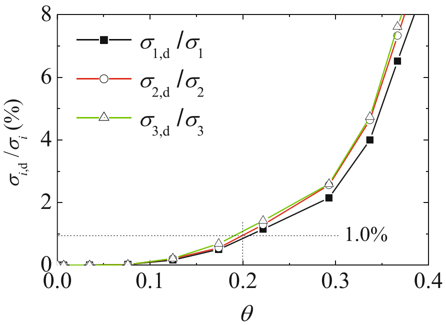

Fig. 4. Contribution of detached particles to the overall stress

The damage variable θ can be inserted into a constitutive model for cemented soil while its association with the measurable shear modulus allows the determination of the damage evolution law. This issue deserves further study.

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