Review on Discrete Element Modelling of Granular Soils

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ABSTRACT

This paper summarizes the recent research done using the Discrete Element Method (DEM) involving granular soils. The review begins by explaining the discrete nature of soil and the difficulties encountered when attempting to model their inherent characteristics, the different continuum and discontinuum methods available. The significance of laboratory testing and the essence of numerical modelling of laboratory testing are discussed. Then, the state-of-the-art associated with numerical modelling of the response of granular soils is presented in detail. Finally, the outstanding issues in the topic are listed and the research gaps that need to be addressed are highlighted.

KEYWORDS: Discrete Element Method (DEM); continuum; discontinuum methods

INTRODUCTION

Granular materials, such as soils, are highly non-linear, and their response is to be recorded at multiple scales (temporal and spatial) to understand the inherent behavior and their interactions [1, 2]. The usual state of granular systems is metastable, which is far from equilibrium. They can be activated with vibrations, shear, external volume forces (such as gravity, electric and magnetic fields), and motion of the interstitial fluid or gas (e.g. water or air) [3]. Such driving forces can induce transitions between solid and fluid. By nature, the length scales involved in these contact interactions are much smaller than the particle size. External loading leads to particle deformations as well as particle rearrangements [4].

In geomechanics, soils such as gravel, sand or non-plastic silts that have zero cohesive strength are granular in nature and are called ‘granular soils’ [5]. The overall behavior of the soil composite is significantly influenced by the material parameters such as stiffness of the particle, nature of fluid filling the voids, grain geometry etc. For example, in dry sand, only repulsive forces exist between the particles, whereas in wet sand, both adhesive and cohesive forces act. Granular soils can wither flow or maintain an inclined surface and form a pile in a specific state [6]. When this state is disturbed by any external force, it may lead to disastrous situations, such as avalanches/landslides, cyclic mobility and flow liquefaction [7]. Liquefaction damage during earthquakes can be prevented if the performance of liquefiable soils and its interaction with structures can be predicted beforehand. Although there has been significant development in laboratory testing (e.g. centrifuge and 1-g model tests), phenomena such as liquefaction are dictated by micro-level mechanisms. The scale at which uncertainties and deformations occur in granular materials is significant and therefore it is required to model them. Analytical methods consist of assumptions, such as elasticity, isotropy, homogeneity, time independency etc. are not generally true in reality, especially when considering granular materials [8]. Analytical methods are useful in geomechanics to provide results with limited effort and identify the variables the affect the problem solution [9]. On the other hand, numerical simulations facilitate the study of phenomena which cannot be predicted by analytical methods and inaccessible to experiments [10]. To understand the micromechanical interactions that cause the failure in granular materials like soils, one needs to take the aid of numerical simulations.

DISCRETE ELEMENT MODELING (DEM)

Most of the numerical methods can be divided into macro-scale continuum framework and micro scale discontinuum [2]. These can be further categorized as mesh or grid-based and meshless methods (Figure 1). Mesh based continuum methods are Finite Element Method (FEM), Finite Difference Method (FDM) and Boundary Element Method (BEM). Recently, meshless/mesh-free/element-free continuum methods were also developed (e.g. smooth particle hydrodynamics [10, 11], diffuse element method [5, 12], element-free Galerkin method (EFG) [13], finite point method [1, 14], etc.) The drawbacks of continuum-based methods are that they are incapable of simulating large deformation problems mostly encountered in geotechnical engineering. The instability is termed as 'element locking' caused by the distortion of the mesh [5]. The interpolation functions used in these methods predict the accurate solution when the meshes are of regular shapes.

Discrete Element Method (DEM), Discrete Fracture Network (DFN) method, and Discontinuous Deformation Analysis (DDA) are some of the popular discontinuum methods currently being employed [14, 15]. In all the numerical methods, the difficulty arises from the conceptualization of the physical process. Selection and application of each method depends on the type and importance of the problem. The relevance of a method to specific problem depends on the size, scale and discontinuities involved. A suitable simulation method considers all the factors related to both the force and geometry [2]. In the case of granular soils, it is straight-forward to treat them as discrete models due to their discontinuous nature.

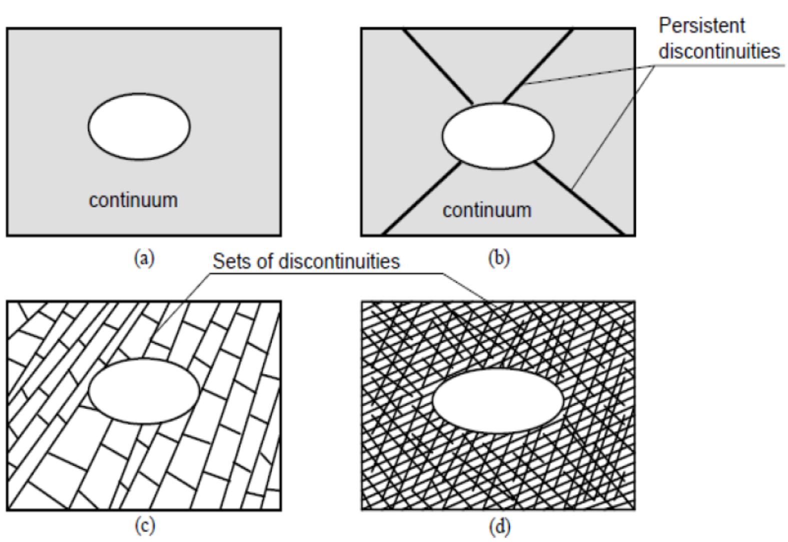

Figure 1: Selection of different numerical methods: (a) continuum method; (b) continuum with fracture element or discrete method; (c) discrete model; and (d) continuum method with equivalent properties [2].

The most notable method of all the discontinuum methods is the Discrete Element Method (DEM) proposed by Cundall and Strack [15] and first formulated by Cundall [16] for application in rock mechanics [10]. In DEM, the deformation between the contacts between the components of a considered system evolve continuously rather than being constant like in the case of continuum methods (Figure 2). Instead of grids, DEM tracks a set of particles modelled at regular intervals of critical time (calculated from the material properties).

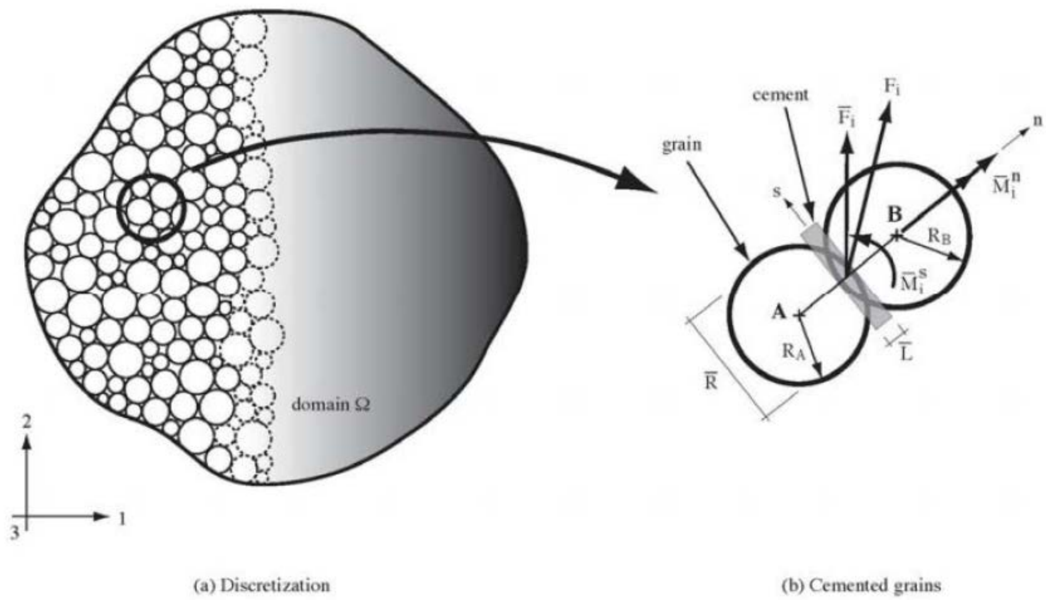

Figure 2: Particulate DEM model [14].

The application of DEM is diverse and various phenomena in the fields of geotechnics, powder technology, mining, metallurgy, pharmacy, agriculture, space research (moon and Marxian regolith), structural analysis, rock mechanics, fluid mechanics, energy production, computer animation, materials (concrete engineering, rock mechanics, soil dynamics), and multi-body systems [4, 5, 12, 17-22] have been modelled using this method. Such varied applications of DEM are due to the modelling capabilities provided by the method. Real material properties, such as particle morphology (shape, size, surface), joints, cementation, orientation and state can be exactly represented in the implementation [14].

In the classical discrete element method, the computations are governed by two laws: Newton’s second law of motion and force-displacement law [23]. The contacts of each particle are detected and using the relative position of each particle, the contact forces acting on each particle are evaluated using the force displacement law [17]. Solving the set of equations takes very small computational time and also the information to be stored occupies very small space. Nevertheless, the time taken for detection of contact type (edge-edge, face-face and edge-face) and the type of bond is significant in terms of the algorithm adopted during execution [3]. Various approaches have been proposed to identify the contacts, such as global search algorithm, contact or field zone, binary tree structures, buffer zone definition, space decomposition, altering digital tree etc. [2, 11, 15, 18]. the law of motion is used to calculate the acceleration and moment acting on the particle, which is then integrated to obtain the particle velocity. The execution of both equations constitutes a calculation cycle. The particle velocities and positions are updated by using different integration methods, such as leap-frog integration, Verlet integration, Beeman's algorithm etc. [14].

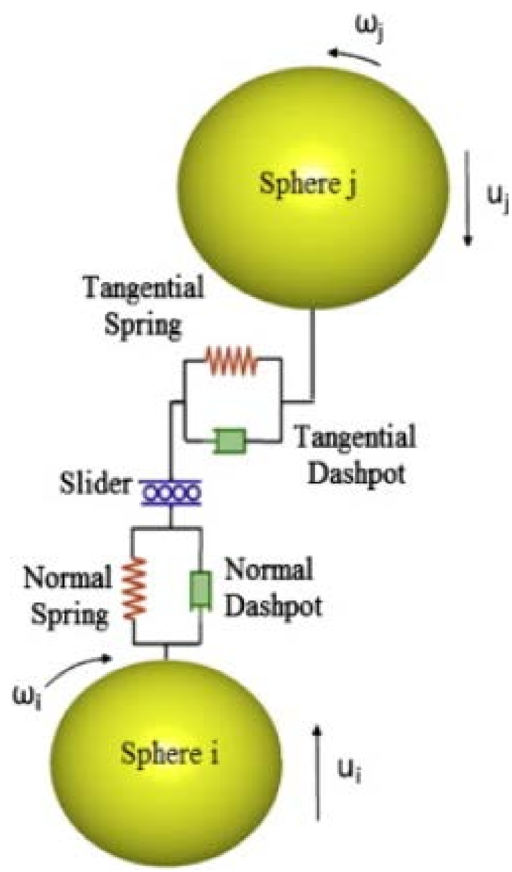

Figure 3: Schematic of the constitutive law of normal and shear contact forces between two particles [7].

VALIDATION

Validation of a numerical model is necessary to prevent any hardware sensitivity error in the simulation and to check the correct implementation of the algorithm [24]. It can be performed analytically or experimentally [9]. By analytically validating the code, one can get the information on the performance of the model, whereas experimental validation or verification confirms whether the physical material response is captured or not [23]. Most of the previous studies [15] were performed using photo-elastic particles. Comparison of images of particle motion during DEM simulation and during experimental testing can be done. These methods necessitate high spatial and temporal resolution images [25]. Also, they validate the DEM code at particle/micro scale [4]. When simulating the laboratory tests, the initial stage involved is the consolidation of the specimen. This is usually achieved by employing the servo control algorithm [22]. To assess the success of the servo-control algorithm, the target stress and actual stress are to be plotted as output and comparison can be made. This is suitable for the DEM simulation with rigid walls [26]. To ensure if the forces applied along the boundaries are in equilibrium, in case of a triaxial simulation, the total force at the bottom boundary must be equal to the total force at the top boundary throughout the simulation.

The results obtained in DEM simulations are very sensitive to the initial geometry of the specimen or system to be analyzed [8]. To be as realistic as possible, the number of particles in the simulation are limited [27]. It is also computationally intensive to exactly replicate the shape and size of the laboratory specimens in DEM [25]. A sample in the size of millimeters even contains millions of particles. The response of smaller samples is more sensitive to small variations in the distribution as compared to larger samples [5]. From theoretical knowledge, it is understood that as long as the specimen slenderness ratio is maintained at 2 (typical geometric ratio used in the experiments), the results of the discrete model do not depend on the characteristic size of the discrete elements [28]; local parameters take this into account [6]. For the validation of undrained simulations, the key characteristics of any undrained simulations that are evident during laboratory tests are to be checked for [17]. For example, for undrained tests on sand, the denser samples dilate with a reduction in excess pore water pressure resulting in an increase of the mean effective stress [25]. In case of looser samples, a phase transformation point marking a transition from dilative to compressive behavior is to be observed. In simple terms, the loose samples get compressed and generate positive excess pore water pressure while dense samples generate negative excess pore water pressure [7].

When performing tests on soils, the model can be validated for confining pressure-dependency and density-dependency. Deviatoric stress and volumetric strain increase with the increase in confining pressure [19]. Dense assemblies undergo large dilation when compared to loose specimens. Thus, the plots for deviatoric stress and volumetric strain are required (Figure 3). The coordination numbers change with the strains which can also be tracked for differently degree of packing (dense and loose) [21]. To validate the undrained cyclic laboratory tests (for liquefaction), the build-up in excess pore water pressure and decrease in effective stress as the number of load cycles are progressed can be recorded [1]. In case of cyclic laboratory testing, evaluation of shear modulus and damping ratio at different strain ranges can be validated with the laboratory results (Figure 4) [14].

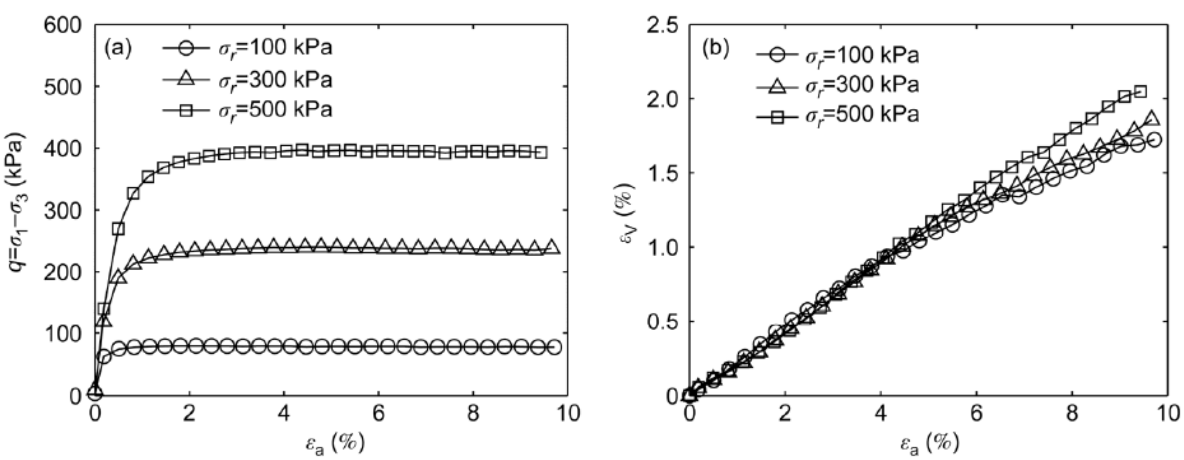

Figure 4: DEM simulation of the triaxial extension of Chende sand under different confining pressures: (a) Stress-strain behavior; (b) volumetric strain-axial strain response [29].

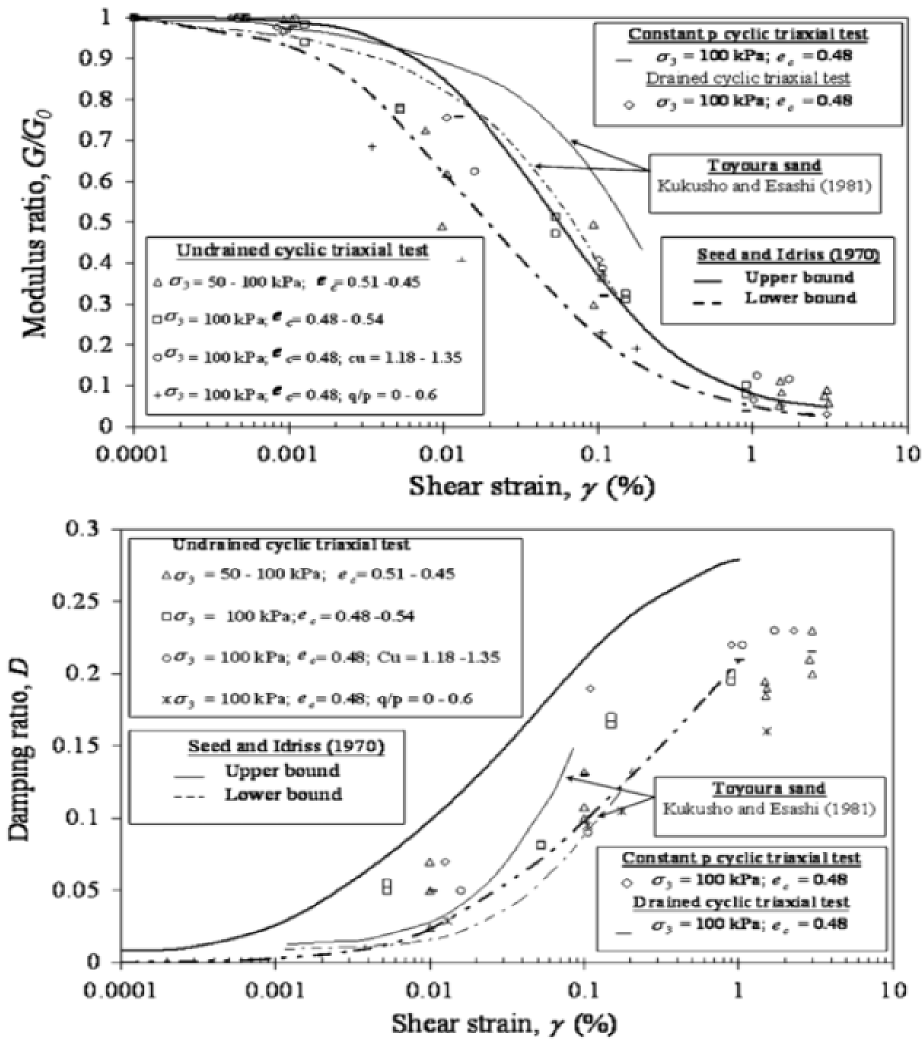

Figure 5: Comparison of shear modulus and damping ratio obtained from numerical tests with standard curves [30].

DEM APPLICATIONS IN GEOTECHNICAL ENGINEERING

After the pioneering work of Cundall and Strack in developing the first discrete element scheme for analyzing particulate and granular media [3, 15, 16], researchers started evaluating and improving the technique. Dobry and Ng [11] performed a literature survey of publications which have used the DEM of compliant particles or blocks for simulations of granular media during the years from 1982-1992. A major conference conducted by the American Society of Civil Engineers (ASCE) in 2002 in New Mexico, USA, presented several major trends in the DEM modelling and practice [1]. Participants discussed and analyzed several topics in this field, including the following:

1) Theory and algorithms: [18, 26, 31];

2) Model generation: [19, 31, 32];

3) Simulation environments: [17, 33, 34];

4) Solid continuum and discrete element methods [7, 13, 35];

75) Fluid discrete element methods: [27, 36, 37];

6) Experimental validation: [20, 22, 23];

8) Granular mechanics: [25, 38];

9) Powders and soils: [8, 28, 39];

10) Rock: [12, 34, 40].

They showed that the model reproduced many features of rock behavior including elasticity, fracturing, acoustic emission, damage accumulation producing material anisotropy, hysteresis, dilation, post peak softening and strength increase with confinement. Matar et al. [41] modelled the evolution of particle subdivision in Montmorillonite clay using 3-dimensional DEM. They wrote a program using ANSI C++ that studied the swelling and swelling pressure response with various amounts of particle breakdown in a unidirectional swelling cell [41]. Chen et al. [42] performed a 3-dimensional modelling of sinkhole repair using the DEM. They showed that the DEM was a reasonable method to investigate sinkhole repair procedure. More recently, researchers used the DEM to model geosynthetic reinforced soils [2], geotextile reinforced soils and geogrid reinforced soils [43]. In the area of extra-terrestrial geotechnical engineering, Schwartz et al. [48] used the DEM in a simulation to model the contact forces between particles in granular materials. Moreover, Lichtenheldt and Schafer [44] developed a simulation model for planetary exploration using 3-dimensional DEM. They developed an inter-particle contact model and showed that the newly developed model is applicable to control soil-interaction problems. Kulchitsky et al. [45] used the DEM in the numerical modelling of void ratio (packing density) to simulate lunar regolith properties. They used the DEM in the simulation of boulder extraction from an asteroid and developed an equation linking the pulling strength to the boulder diameter. Manne and Satyam [14] reviewed in detail the discrete element modelling of dynamic laboratory tests for liquefaction assessment. They identified gap areas in these laboratory tests related to numerical modelling.

CONCLUSIONS

This study concludes that the application of the DEM method to various rock and soil materials was found to be most promising and adequate. The limited amount of work done on simulating geotechnical applications also appears to be going on the right track with initial reliable results. The DEM method seems to be the most adequate for particulate systems. Based on the research studies conducted on the laboratory testing and numerical modelling of granular soils, the gap areas in terms of numerical modelling can be summarized as follows:

- The simulations of 3D cyclic triaxial experiments on sand specimens need further examinations. Research gaps were observed in the consideration of the effect of particle shape and grain size distribution on the micro-mechanical response and liquefaction resistance.
- Investigation of the influence of particle crushing on the liquefaction occurrence in crushable soil deposits need more examination.
- Further evaluation of the micro-mechanical characteristics, such as co-ordination number, contact density, contact normal, contact force etc. at various stages of the liquefaction phenomenon.

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