Chapter 7

Conclusions

Central to many geotechnical engineering designs is the problem of determining how the local interactions between granular soils and man-made inclusions govern the overall behavior of a composite system. The *interphase*, the link between the matrix soil and construction material, is defined as a local region near a solid manufactured inclusion or natural surface that consists of granular soil and the inclusion surface. The interface, as normally discussed in geotechnical literature, is the boundary between the interphase soil and the inclusion or natural surface. Conventional designs primarily rely on empirical or semi-empirical correlations between interface frictional resistance and types, hardness and mineralogy of soils and structural materials. These usually provide only preliminary and rough estimates of interface friction for designs. The main reason for this, is that, there is incomplete understanding of the physical principles governing the interphase behavior. This resulted in few predictive relationships for interfaces available to the practice community that account for surface and soil properties. This deficiency in current practice has seen increasing importance because innovative applications are arising which require close control over the interface friction, and have operational interphase strengths less than the maximum values.

This dissertation has presented results of a study which addresses the above problems through two dimensional DEM simulations of interphase systems. The effects of particle to surface relative geometry, particle to surface friction and particle size distribution on interphase behavior are the main focus of this research. The numerical model allows easy access to a substantial body of microscopic information, which provides unique insights into the micromechanical interphase behavior in both a qualitative and quantitative manner, and is essential for the identification of physical principles governing the interphase strength and deformation behavior. The results of numerical modeling are used to develop a failure criterion for interphase systems composed of spherical particles. Publications resulting from this research are significant and original contributions to the geoengineering, material science, geophysics and granular physics literature.

Six major conclusions are drawn from this research and are addressed in subsequent sections. In summary, these include: (1) boundary effects and particle rolling resistance have the greatest influence on micro and macro mechanical behavior; (2) a micromechanics-based framework, interpreted using continuum methods is essential for quantitatively describing the mechanical response of an interphase system; (3) direct shear strength and volume change behavior can be accurately simulated with discrete element methods; (4) the rough surface controls shear band orientation and thickness; (5) evolution of fabric and contact force anisotropy at the boundary between the surface and the granular media has exclusive control on interphase shear behavior; and, (6) an interphase failure criterion based on the principal direction of the resultant contact force orientation is able to account for varying relative particle to surface geometry.

7.1. Conclusions regarding model development

It is concluded that boundary effects and particle rolling resistance are two major factors influencing the model behavior discussed in Chapter 2. An appropriate DEM interphase model displaying physical soundness and realistic mechanical behavior was established by addressing these two factors.

Four model physical variables, namely length of frictionless zone, boundary friction, model height and initial fabric are identified which show significant influence on system behavior. The first three of these variables are found to affect model behavior by imposing boundary constraints in different ways. In order to reproduce microscopic as well as macroscopic interphase behavior similar to those observed in the laboratory or filed, one must create boundaries in a model with geometric and physical settings that reproduce the similar degrees of constraint on the interphase soils to those in real life. The boundary effect, besides elastic properties of granular particles and surfaces, plays an essential role in the correct and realistic simulation of interphase behavior.

Particle rolling, as identified as a major microdeformation mechanism of granular material, is shown to have great importance on both the macroscopic and microscopic interphase shear behavior. Rolling resistance raises the peak strength ratio and governs the dilatancy behavior of the interphase system. More importantly, rolling resistance is essential for the evolution of the shear band, which is practically invisible in the free rolling case. Therefore rolling resistance must be incorporated into the DEM interphase model.

7.2. Conclusions regarding micromechanics-based framework

A micromechanics-based framework is formulated using theories of shear-induced anisotropy and homogenization of granular material. Using this framework, we are able to interpret the mechanical behavior of granular media from a continuum point view using the discrete data collected from the DEM simulations. This approach has great advantages as compared to conventional continuum-based methods in that the deformation and strength behavior of granular media can be determined and described in a more accurate manner due to the discrete data recorded at a higher resolution. In addition, a substantial body of microscopic information interior to the sample can be made useful for gaining further insights into the full picture of mechanical behavior of the entire granular assemblage.

Interpretations of mechanical behavior using this discrete-continuum approach in both direct shear simulations and direct interface shear simulations have proven highly effective, uncovering many facts related to the microscopic origins of macroscopic strength and deformation behavior. Therefore it is concluded that this micromechanics-based framework is inevitable for identifying the physical mechanisms underlying the interphase behavior and must be adopted in this research.

7.3. Conclusions regarding direct shear test simulations

Studies on direct shear test simulations are important for this research because they serve as a baseline for the interphase shear test and the knowledge of direct shear behavior is indispensable for the understanding of interphase shear behavior.

Anisotropies of fabric, contact normal force and contact shear force increase and rotate significantly after shearing starts, and reach their maximum at peak state. Strain localization is found to initiate from the side boundaries due to geometric constraints and extend towards the middle of the box after displacement begins. Shear bands in dense samples are more continuous, concentrated and uniform than those in medium dense samples.

An extended Rowe-Davis framework is developed that describes the internal stress, dilatancy and shear banding characteristics of granular soils in the general case where non-coaxiality behavior and non-horizontal zero linear extension exist. Peak and critical state data from simulations are found to be in good agreement with the extended flow rule. Better agreement is obtained when the effect of non-coaxiality is taken into account. This effect is important during pre-peak shear displacement as significant stress rotation takes place. The shear band orientation predicted from the Roscoe equation suggests deviation of zero linear extension direction from the horizontal at peak state is less than 3 degrees. Therefore, the volume change measurements made at the boundary of the DSA should reflect the volume changes occurring in the sample.

7.4. Conclusions regarding interphase shear banding behavior

A simple new numerical-based method of strain calculation, which employs a grid type discretization over the volume of whole assemblage and calculates the displacements of each grid point by assigning each grid point to a particular particle, is used in this research to generate strain field inside the interface shear box. The calculated strain filed is found to clearly outline the overall shape of shear localization zone and capture the characteristics of rupture bands more accurately than other methods.

It is found that for a regular surface, a series of rupture bands emerge in a sequential way to form the major and subordinate structures of the final shear zone at the post peak stage. The irregular surfaces tend to develop irregular zones of shear localization due to spatial distribution of surface roughness along its surface length, but the structure of rupture bands within each local shear zone is similar to that of a regular surface. The surfaces with greater roughness will generally sustain higher stress ratios and develop thicker shear bands. The surfaces which can fully mobilize the material strength will develop the most intense shear band with maximum thickness of about 8 to 10 median particle diameters. Analyses of shear band orientation show that the effect of lower boundary movement is dominant, and Roscoe solution gives the best theoretical predictions both in the overall and local interphase regions.

7.5. Conclusions regarding interphase strength behavior

A new approach considering the actual particle to surface contact has been adopted to explore the physical principles underlying the interphase strength behavior. It is found that the evolution of fabric and contact force anisotropy at the boundary between the surface and the granular media has an exclusive control on the shear behavior. Full mobilization of granular material strength occurs when the contact force anisotropy developed at the interface is equal to the maximum contact force anisotropy of the granular media.

A unique bilinear relationship exists between the principal direction of average contact resultant force anisotropy and mobilized granular media strength. This relationship is independent of particle to surface friction coefficient. Interphase strength increases with increasing obliquity of the principal average contact resultant force direction. Similar bilinear relationships that are functions of particle to surface friction coefficient hold for the principal direction of average contact normal force anisotropy. These findings show that the problem is governed by material-to-material contact, and not purely by geometry as previous research has presumed.

7.6. Conclusions regarding interphase failure criterion

Having understood the fundamental mechanisms governing the interphase strength behavior, a new, practical failure criterion has been developed based on principal direction of surface normal distributions determined from profiles of median particle centroid trace. This failure criterion prevails over the traditional correlations based on normalized roughness parameters in that it covers the full range of relative particle-surface roughness and accurately predicts the interface strength behavior by filtering out the non-dilative portions of surfaces which contribute little to the macroscopic strength behavior.

Good agreement with the results of laboratory interface shear test data is observed and it appears valid for rounded and sub-rounded particles. For the extreme case of profiles with constant discontinuous asperity spacing, additional correlations are provided that extend the range of surfaces that can be used.

7.7. Recommendations for future research

Important factors that will impose great effects on interphase behavior but are not covered in this research include grain shape, grain to surface relative hardness, grain crushing and fluid effect. The mechanisms uncovered in this research should still work but the failure criterion may need modification when these factors are considered due to more complex contact behavior and plastic contact deformation. In addition, 3D simulations are an urgent need for understanding the real micromechanical behavior and extending the current results into full three dimensions. It is anticipated that the failure criterion in 3D condition would assume the same format but need more complex correlations to account for particle to surface contact conditions.