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A new probabilistic approach for predicting particle crushing in one-dimensional compression of granular soil

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Abstract

This paper presents a new probability-based method for the prediction of particle crushing in the one-dimensional compression of granular soil. The method is comprised of a joint-probability particle crushing criterion that takes into account the statistical particle-scale stress distribution information derived from the Discrete Element Method (DEM) simulations and Weibull's distribution of particle crushing strength. A normalized tensile stress index f and a diameter index I_d are introduced to quantify the statistical particle-scale data. The method is further implemented in DEM simulations and verified by comparing the simulation results with the experimental data of oedometer tests of sands.

Keywords: Particle crushing; Particle-scale stress distribution; Joint-probability crushing criterion; Discrete Element Method

1. Introduction

Particle crushing plays an important role in the mechanical properties of granular soils. A complete and thorough understanding of the macromechanical behavior of crushable sands and its underlying micromechanical principles is a prerequisite to the development of a new generation of physically rigorous constitutive models of sands. Despite the significant amount of research efforts devoted to this subject (e.g., Bolton, 1986; Cuccovillo and Coop, 1999), great difficulty still exists in the theoretical quantification and prediction of particle crushing, particularly when the influences of a number of particle-scale factors such as particle size/shape, fracture strength, soil grading, applied stress condition, etc., are to be accounted for.

By means of various types of laboratory tests, a rich body of knowledge has been gained over the years. For example, Luzzani and Coop (2002), Coop et al. (2004) and Bandini and Coop (2011), by using the breakage ratio (B_r) first proposed by Hardin (1985), revealed the relationship between particle breakage and the critical-state response of sands through a series of triaxial and ring shear tests. In their tests, the soil reached a stable grading at very large displacement, but the final grading was found to depend on the initial grading and the applied external stress. A series of oedometer tests conducted by Altuhafi and Coop (2011a, 2011b) clearly showed that a much larger amount of particle breakage occurred in poorly-graded samples than in well-graded samples and this trend continued to

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a point where no significant particle breakage could be measured in very well-graded samples. By testing the well-graded silica sand, Nakata et al. (2001) found that bigger particles were more susceptible to asperity breaking and surface grinding, while smaller particles were more susceptible to major splitting. Due to the limitation of experimental techniques, what happens inside the sand and why this phenomenon occurs are not clear. Two opposite trends about the particle crushability within a loaded sand that need to be considered are as follows: large particles are safer because they tend to have more contacts than surrounding particles, whereas small particles are more difficult to break than large particles due to their higher average fracture strength. For well-graded samples, an internal dynamic balance might be established, leading to a stable state.

By assuming that the sand crushing produces a soil grading which obeys the fractal geometry, McDowell and Bolton (1998) derived a theoretical relationship between the 1D compression rate of a sand and its fractal geometry of grading. The most important assumption of the fractal theory is that it is the smallest particles that continue to fracture under the increasing macroscopic stress, and that the probability of fracture of the smallest particles is a constant. A conceptually different approach taken by Nakata et al. (1999) to predict the particle breakage within a triaxial sample was based on the statistical distribution of single particle fracture determined from single particle crushing tests, but an ad hoc assumption was made to estimate the particle-scale stress condition for the breakage prediction purpose. The assumptions adopted in the above studies, however, lack of supporting experimental evidence and are questionable because the particle-scale stress distribution within a loaded sand could be highly non-uniform. Einav (2007a, 2007b) developed a new continuum breakage mechanics theory for the constitutive modeling of brittle granules, using the relative breakage ratio as the damage internal variable; however, the micromechanics of particle breakage were not considered in his research.

In recent years, more sophisticated investigations into the particle breakage behavior within a loaded granular soil using the X-ray CT technique have emerged. The high-resolution CT images offered by laboratory nanofocus scanners or synchrotron sources allow the identification of inter-particle contacts and the quantification of sand fabric (e.g., Hall et al., 2010; Hansan and Alshibli, 2010; Andò et al., 2012; Fonseca et al., 2013). It is possible, therefore, to evaluate the effects of particle breakage on the evolution of sand fabric and particle size distribution within a granular system. However, an inherent limitation of the CT technique is the unavailability of the information of inter-particle contact forces within the system, which is necessary for a complete understanding of the breakage mechanics. Towards a more physically sound modeling of particulate materials using the Discrete Element Method (DEM), some researchers have recently started the accurate experimental measurement of the load–displacement relationship of the contact between two sand particles (e.g., Cole and Peters, 2007; Cavarretta et al., 2010; Senetakis et al., 2013), which is expected to improve the current DEM method by offering more realistic and effective particle contact laws. Such a type of research is often tied to the study of breakage mechanics because the loading of a contact frequently involves the local damage, fracturing or even major splitting (depending on the contact displacement magnitude) of the two contacting particles. However, considering the highly complex particle characteristics that can affect the inter-particle contact and particle breakage behaviors, such as particle size, morphology, microstructure, contact surface roughness, etc., significant efforts will be needed before any breakthrough understanding of the particulate mechanics can be achieved.

As an alternative to the investigation of fundamental sand behavior, the Discrete Element Method first proposed by Cundall and Strack (1979) has made significant contributions towards unraveling the microscopic mechanisms of crushable soil behavior over the past two decades. In tackling the simulation of crushable soils, two common approaches exist in the literature: particle cluster approach and particle multiplication approach. The first approach bonds a group of elementary spheres together to form a porous agglomerate which can disintegrate to simulate particle breakage. It was used by a number of authors (e.g., Robertson, 2000; Cheng et al., 2003, 2004; Bolton et al., 2008; Wang and Yan, 2011, 2012) to investigate a wide range of fundamental soil behavior including soil yielding, plastic deformation, fractal crushing, strain localization and particle-scale energy allocation. The second approach, proposed by Lobo-Guerrero and Vallejo (2005a, 2005b), simulates particle breakage by replacing the original sphere by several smaller spheres. It was much less popular than the first approach, mainly because of the difficulty of establishing a physically sound breakage criterion for the prediction of particle breakage. However, the potential of this approach will be exploited in the current study through the construction of a theoretically robust and numerically efficient particle breakage criterion.

Another innovative and relevant method to predict particle breakage recently proposed by Marketos and Bolton (2007, 2009) was based on the statistical distribution of inter-particle contact forces derived from DEM simulations. The prediction and quantification of particle breakage were made possible by assuming a known distribution of single particle crushing strength and using a crushing criterion which depends on the maximum contact force acting on a particle. The effects of initial sample grading and relative density on the particle breakage evolution, however, were not considered in that study.

Based on the work of Marketos and Bolton (2007, 2009), a new statistical method which evaluates the probability of particle crushing by taking into account the statistics of both particle-scale stress distribution and characteristic fracture strength is presented in this paper. The theoretical formulation is further implemented in the DEM simulations of 1D compression of granular soils. The effectiveness and validity of the theoretical and numerical models are demonstrated by comparing the simulation results with the available experimental data.