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Critical state shear behavior of the soil-structure interface determined by discrete element modeling

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ABSTRACT

The interface between soil and structure can be referred to as a soil-structure system, and its behavior plays an important role in many geotechnical engineering practices. In this study, results are presented from a series of monotonic direct shear tests performed on a sand-structure interface under constant normal stiffness using the discrete element method (DEM). Strain localization and dilatancy behavior of the interface is carefully examined at both macroscopic and microscopic scales. The effects of soil initial relative density and normal stress on the interface shear behavior are also investigated. The results show that a shear band progressively develops along the structural surface as shear displacement increases. At large shear displacement a unique relationship between stress ratio and void ratio is reached in the shear band for a certain normal stress, indicating that a critical state exists in the shear band. It is also found that the thickness and void ratio of the shear band at the critical state decreases with increasing normal stress. Comparison of the DEM simulation results with experimental results provides insight into the shear behavior of a sand-structure interface and offers a means for quantitative modeling of such interfaces based on the critical state soil mechanics.

Introduction

The interface between soil and structure is very important in geotechnical engineering with respect to constructing pile foundations, retaining walls, and earth reinforcement. The soil-structure interface has therefore been widely studied because the mechanical behavior plays a crucial role in the overall behavior of the soil-structure system. Many experiments have been conducted to investigate the behavior of the interface between different soils (sand, clay, gravel) and construction materials (steel, concrete) under different load types (monotonic, cyclic) and boundary conditions (constant normal stress, constant normal stiffness, constant volume) (Brumund & Leonards, 1973; DeJong, Randolph, & White, 2003; Desai, Drumm, & Zaman, 1985; El Cheikh, Rémond, Pizette, Vanhove, & Djelal, 2016; Fioravante, Ghionna, Pedroni, & Porcino, 1999; Ghionna & Mortara, 2002; Kishida & Uesugi, 1987; Martinez & Frost, 2016; Peng, Ng, & Zheng, 2014; Potyondy, 1961; Shahrour & Rezaie, 1997; Tejchman & Wu, 1995; Uesugi & Kishida, 1986a, 1986b; Uesugi, Kishida, & Tsubakihara, 1989; Yoshimi & Kishida, 1981; Zeghal & Edil, 2002; Zhang & Zhang, 2006).

Various experimental methods have been used in such interface shear tests, with direct shear tests and simple shear tests being the most commonly used. More modern and advanced techniques such as photography (Hu & Pu, 2004; Uesugi, Kishida, & Tsubakihara, 1988), radiography (Tejchman & Wu, 1995), and particle image velocimetry (PIV) (DeJong et al., 2003) have been incorporated to further explore the fundamental mechanisms related to soil-structure interface behavior.

Previous investigations have revealed that the behavior of a sand-structure interface may be affected by factors such as surface roughness, soil relative density, particle shape, grain size, soil mineralogy, and normal stress level (DeJong & Westgate, 2009; Uesugi & Kishida, 1986b).

Uesugi et al. (1988) and Hu and Pu (2004) showed that a smooth interface follows an elastic-perfectly plastic failure mode and the shear stress and volume change maxima are reached at a very limited interface displacement with very little dilatancy near the interface. Conversely, strain localization occurs in a thin layer of sand, a shear band, adjacent to the structural surface associated with large dilatancy for a rough interface. The interface consists of a strain-localized zone together with a contacting surface, and its

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height is usually referred to as the thickness of the interface (Uesugi et al., 1988). It has also been revealed that the thickness of the interface shear band does not correlate with a certain range of values but can be normalized by the mean particle size (D_{50}) of granular soil (DeJong & Westgate, 2009; DeJong et al., 2003; Uesugi et al., 1988; Yoshimi & Kishida, 1981). The ratio of shear band thickness to D_{50} varies approximately in the 5–10 range; the exact value depending on the particle angularity, crushability, and surface roughness. It is interesting to note that the thickness of the interface shear band is about half of that formed in soils in laboratory tests, e.g. 10–20 times that of mean particle diameter (Mühlhaus & Vardoulakis, 1987; Roscoe, 1970).

It has been shown that the density-dependent and stress-dependent characteristics of the interface between sand and a rough structure are very similar to those of granular soil. Boulon and Nova (1990) discussed the applicability of soil constitutive models to a rough interface and there is also experimental evidence that, at large shear deformation, the interface can reach a steady state at which the stress ratio is constant and no further volumetric changes occur (Fioravante et al., 1999; Hu & Pu, 2004). This phenomenon is reminiscent of the concept of critical state in soil behavior, although it is not yet well understood how a strain-localized zone progressively forms at the soil-structure interface and develops to the critical state, especially at the soil particle scale. The evolution of soil behavior out of the strain-localized zone is also not known.

The discrete element method (DEM) proposed by Cundall and Strack (1979) is a suitable and powerful tool for investigating the macroscopic behavior of granular material at the microscopic scale, especially for displacements and rotations of large particles. The DEM is advantageous for conveniently analyzing the evolution of soil microstructure and facilitates sample reproducibility. A number of DEM simulations have been performed to explore the soil-structure interface behavior at the microscopic scale. Jensen, Bosscher, Plesha, and Edil (1999), Jensen, Edil, Bosscher, Plesha, and Kahla (2001) and Jensen, Plesha, Edil, Bosscher, and Kahla (2001) studied the effects of surface roughness, particle shape and particle breakage using DEM in which periodic lateral boundaries were used and the particles were represented by three-spheres combined clusters. Their results showed that the displacement field of the particles was significantly affected by the interface roughness and the particle shape. As the particle angularity increased, particle rotation became more constrained, resulting in increased strength and the suppression of a well-defined shear zone. It was also found that grain crushing led to a more distinct shear zone without significant reduction in shear strength of the granular soil.

Frost, DeJong, and Recalde (2002) conducted a series of DEM interface shear tests to investigate the effects of surface roughness and hardness on the shear behavior of a soil-structure interface. Wang, Dove, and Gutierrez (2007) conducted direct shear tests along an interface of densely packed spherical particles and a rough structural surface. The results showed that the mobilization of the interface strength was related to the development of fabric anisotropy and contact force anisotropy at the contacts between particles and the boundary. Using a strain calculation method considering the particle rotation, Wang, Gutierrez, and Dove (2007) also studied the initiation and development of a shear band. Peng et al. (2014) investigated the behavior of the interface between sand and piles using a series of DEM direct shear tests under various boundary conditions. The results showed that the initial normal stress and relative density of the surrounding soil affects the mobilized stress ratio and normal stress increment of the interface. Ngo, Indraratna, and Rujikiatkamjorn (2014) studied the interface behavior of a geogrid-reinforced ballast fouled with coal under direct shear using DEM and clumps of irregular shapes were employed as particles. Martinez and Frost (2016) made a systematic comparison between interface behavior under axial loads and torsional loads using DEM simulation in which global- and particle-scale behaviors were revealed to have contributed to a comprehensive understanding of interface behavior. El Cheikh et al. (2016) simulated the shear behavior of spherical particles between two rough-surfaced walls and revealed how the shear velocity, wall roughness, and concentration of rough areas along the wall affected the effective friction coefficient and shear localization of the interface. However, there are few DEM simulations that investigate the effects of initial normal stress and soil density on interface behavior, although it is well agreed that they significantly affect the behavior of granular soil. Most importantly, how the soil-structure interface progressively develops into a shear band and finally reaches the critical state as observed in laboratory experiments has not been well known. It is also meaningful to investigate the characteristics of the interface shear band and the state of soil both within and outside of the shear band.

In this paper, a series of DEM simulations of monotonic direct shear tests on the interface between sand and a rough surface are performed. The aim of these simulations is to investigate macroscopic shear behavior at the microscopic scale and to analyze the effects of soil relative density and normal stress on the macroscopic responses. The particle displacement field and distribution of the void ratio are also analyzed during shearing to explore the underlying mechanism of strain localization that leads to shear band formation. The distinct evolution of variables in the shear band and in the far-field is also explored to gain insight into the critical state behavior of the soil-structure interface.

Discrete element modeling

The DEM program PFC2D (Itasca, 2002) was used to perform the simulation. The program models the movement and interaction of discrete single circular particles or combined circular particles of arbitrary shape using an explicit time-step algorithm. The motions of particles are determined by Newton's second law and the contact forces are derived from contact constitutive models which include a stiffness model, slip model, and bonding model. Moreover, damping is introduced to dissipate energy and allow mechanical equilibrium to be reached more quickly. More details about the DEM can be found in the PFC2D user manual (Itasca, 2002).

The monotonic interface shear test conducted by DeJong et al. (2003) between medium dense sand and a rough aluminum plate to which sand grains adhered was simulated. Additional simulations with different initial densities of sand, and under different initial normal stresses, were performed. To decrease the stress fluctuations during the strain softening stage, the dimensions of the specimens in the simulations were enlarged to a rectangular space 200 mm wide and 60 mm high, compared to the original width (L) of 100 mm and height (H) of 30 mm. The D_{50} is 0.72 mm, which is the same as in the laboratory experiment. The values of L/D_{50} and H/D_{50} are sufficiently large to diminish the deleterious boundary effects and ensure the full development of a shear band (Jensen et al., 1999; Wang, Dove, Gutierrez, & Corton, 2005). Clumps of two circular particles with an aspect ratio of 1.5 were adopted to consider particle rolling resistance which is critical to the strength and dilatancy behavior inside the shear band of granular materials (Iwashita & Oda, 1998; Oda & Kazama, 1998). The clump cannot break apart throughout the simulation and behaves as a rigid body. In the laboratory test, particles near the interface may break during the shearing and reduce the dilatancy of the soil. Nevertheless, considering the initial normal stress levels (i.e. 100 kPa) in the experiment and the breakage strength of the sand particle, the amount of particle breakage should be very small and therefore the assumption of unbreakable clumps in the DEM simulation are appropriate.