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Discrete simulations of shear zone patterning in sand in earth pressure problems of a retaining wall

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ABSTRACT

The intention of the paper is to check the capability of a discrete element method (DEM) to simulate a pattern of quasi-static shear zones in initially dense sand. Discrete calculations were carried out with a rigid and very rough retaining wall, undergoing passive and active horizontal translation, rotation about the top and rotation about the toe. To simulate the behavior of sand, the three-dimensional spherical discrete model was used allowing for grain rolling resistance. The geometry of calculated shear zones was qualitatively compared with experimental results of laboratory model tests using X-rays and Digital Image Correlation technique (DIC), and quantitatively with finite element results obtained with a micro-polar hypoplastic constitutive model. The results show that a discrete model is able to realistically predict the experimental pattern of shear zones in the sand interior. A satisfactory agreement with experiments and finite element calculations was achieved.

1. Introduction

Earth pressure on retaining walls is one of the soil mechanics classical problems. In spite of an intense theoretical and experimental research over more than 200 years, there are still large discrepancies between theoretical solutions and experimental results due to the complexity of the deformation field in granular bodies near the wall caused by localization of shear deformation (which is a fundamental phenomenon of granular material behavior, Roscoe, 1970; Vardoulakis, 1980; Tejchman and Gudehus, 2001; Gudehus and Nübel, 2004; Tejchman, 2008). It was experimentally observed (Vardoulakis, 1980; Han and Vardoulakis, 1991; Yoshida et al., 1995; Desrues and Viggiani, 2004) that localization can appear as single, multiple or pattern of shear zones, depending upon both initial and boundary conditions. It can be plane or curved. Within shear zones, pronounced grain rotations and curvatures connected to couple stresses, large strain gradients, and high void ratios together with material softening (negative second-order work) are expected. The thickness of shear zones depends on many various factors, as: the mean grain diameter, pressure level, initial void ratio, direction of deformation, grain roughness and grain size distribution (Tejchman, 2008). The knowledge of both the distribution of shear zones and distribution of shear and volumetric strains within shear zones is important to explain the mechanism of granular deformation. The multiple patterns of shear zones are not usually taken into account in engineering calculations.

Earth pressure on retaining walls is usually calculated within a theory of elasticity and plasticity. In plastic limit states, there are generally two approaches: static and kinematic. Within the first approach, assuming the material yielding behind the wall according to the Mohr–Coulomb law, one can obtain mathematically closed solutions of pressure distribution for simple boundary conditions (Caquot and Kerisel, 1948; Negre, 1959). In the case of complex boundary and load conditions, numerical solutions using a characteristics method for stress and velocity fields can be obtained (Sokolovski, 1965; Roscoe, 1970; James and Bransby, 1971; Szczepiński, 1974; Bransby and Milligan, 1975; Houlsby and Wroth, 1982; Milligan, 1983). Within a simpler kinematic approach, based on the force equilibrium, different failure mechanisms consisting of slip surfaces are assumed. From the equilibrium of forces acting on sliding rigid blocks, a resultant total earth pressure force can be calculated (Coulomb, 1773; Terzaghi, 1951; Gudehus, 1978). Theoretical solutions are very sensitive to the angle of internal friction of soil and soil-wall friction angle. They are not able to predict consistently deformations (Leśniewska and Mróz, 2001). Finite element calculations are more realistic than analytical solutions, since first, they take into account advanced constitutive laws describing the granular material behavior, and second, they can

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predict the evolution of localization of deformation. For FE-analyses of earth pressures in granular soils, a perfect plastic (Nakai, 1985), an elasto-plastic (Simpson and Wroth, 1972; Christian et al., 1977; Potts and Fourie, 1984), an elasto-plastic with remeshing (Hicks et al., 2001), a hypoplastic (Ziegler, 1986), and a micro-polar hypoplastic constitutive law (Tejchman and Dembicki, 2001; Nübel, 2002; Tejchman et al., 2007) were used. A characteristic length of micro-structure was not taken into account in the analyses except of calculations with a micro-polar hypoplastic law.

The intention of our paper is to check the capability of a discrete element model (DEM) to simulate a pattern of quasi-static shear zones in initially dense sand. The plane strain DEM calculations were carried out with sand placed behind a rigid and very rough retaining wall, undergoing passive and active movements: horizontal translation, rotation about the top and rotation about the toe. In a passive mode, a retaining wall moved towards the backfill and in an active mode away from it. To simulate the behavior of sand, the three-dimensional spherical discrete model YADE developed at University of Grenoble was used, allowing for introducing grain rolling resistance in order to take into account the grain roughness (Kozicki and Donze, 2008). The attention was laid on the influence of the different wall movement on the characteristic evolution of shear zones. The layout of calculated shear zones was qualitatively compared with corresponding experimental results of laboratory model tests performed by a number of researchers at University of Cambridge employing X-rays (Leśniewska, 2000) and also with some tests made by Niedostatkiewicz et al. (2010) – the latter were recorded using digital photography and subsequently analyzed by Digital Image Correlation (DIC). The experiments with X-rays and DIC were carried out with different sands, granular specimen sizes and initial void ratios. The discrete element (DE) results were also quantitatively compared with the finite element (FE) results obtained by modeling the sand behavior with a micro-polar hypoplastic constitutive model (Tejchman et al., 2007; Tejchman, 2008) for the same sand, its initial void ratio, specimen size and boundary conditions.

The capability of DEM to simulate a single shear zone during plane strain compression, direct and simple shearing was several times confirmed in the scientific literature (Iwashita and Oda, 1998; Thornton and Zhang, 2006; Pena et al., 2008; Ord et al., 2007; Luding, 2008). However, its capability to simulate complex patterns of shear zones in the interior of granulates has not been comprehensively checked yet. This paper is focused mainly on a direct comparison between finite and discrete results at the global level, i.e. with respect to patterns of shear zones and load–displacement diagrams. The comparative study of shear zones at the micro-level using these both different approaches will be published later.

2. Experimental shear zones

2.1. Shear zones recorded by X-rays

Comprehensive experimental studies on earth pressure problem in sand have been carried out at Cambridge University between 1962 and 1974. Two earth pressure apparatuses were employed. In case of the so called ‘small earth pressure apparatus’, the wall was 152 mm high and 152 mm wide (Arthur, 1962). In the remaining cases, the ‘large earth pressure apparatus’ was used, and the retaining wall was 330 mm high and 190 mm wide. The sand used was rounded coarse quartz ‘‘Leighton Buzzard’’ sand (grain size between 0.6 and 1.2 mm, mean grain diameter d_{50} = 0.9 mm) (Cabalar and Cevik, 2010). The evolution of shear localisation in sand was recorded using the radiographic technique

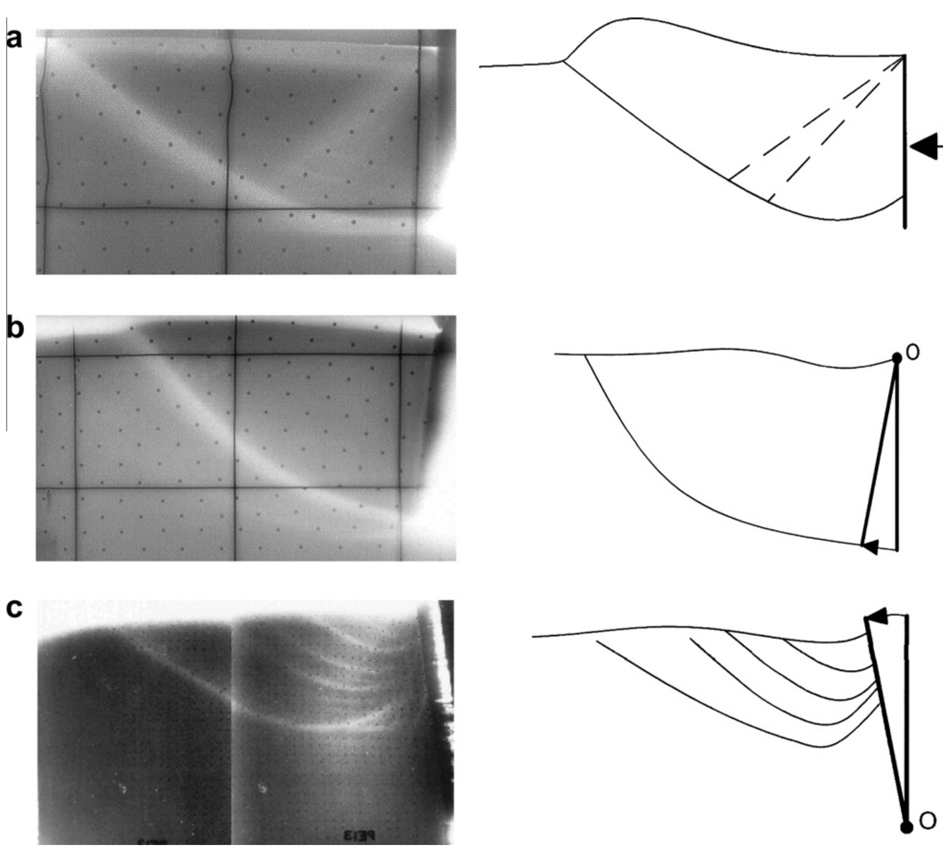

Fig. 1. Shear zones observed in experiments of passive mode with initially dense sand (radiographs and schematically): (a) during wall translation (Lucia, 1966), (b) during wall rotation around the top (Arthur, 1962) and (c) during wall rotation around the toe (Bransby, 1968) (*O* – rotation point) (radiographs from Leśniewska, 2000).