Discrete Modelling of Micro-structural Phenomena in Granular Shear Zones

Michal Nitka, Jacek Tejchman and Jan Kozicki

Abstract The micro-structure evolution in shear zones in cohesionless sand for quasi-static problems was analyzed with a discrete element method (DEM). The passive sand failure for a very rough retaining wall undergoing horizontal translation towards the sand backfill was discussed. To simulate the behaviour of sand, the spherical discrete model was used with elements in the form of rigid spheres with contact moments.

1 Introduction

Earth pressure on retaining walls is one of the soil mechanics classical problems. In spite of intense theoretical and experimental research works over more than 200 years, there are still large discrepancies between experimental results and relevant theoretical solutions. The reason is the complexity of deformation field in granular bodies, especially near the wall, created by spontaneous emergence of shear localizations in a form of single or multiple narrow zones—the fundamental phenomenon characteristic for a granular material at shear deformation.

The patterning of shear zones is usually not taken into account in engineering calculations due to the lack of the basic knowledge on the phenomenon, which gives some practical importance to the research described in this paper. Its objective is to investigate, using the discrete element method DEM, the quasi-static evolution

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of micro-structure within shear zones, created in initially medium dense sand under passive earth pressure conditions created by means of a rigid vertical wall moving towards the granular material. Several characteristic micro-structural events occurring in shear zones at the grain-level, such as: force chains, vortex structures, local void ratio fluctuations, strain non-uniformities were carefully studied.

2 DEM Results

To simulate the behaviour of cohesionless sand, a three-dimensional spherical discrete model YADE was developed at University of Grenoble (Kozicki and Donze 2008) by taking advantage of the so-called soft-particle approach (i.e. the model allows for particle deformation which is modelled as an overlap of particles). Spherical elements were used only. To approximately simulate a grain shape, additional moments were introduced into a discrete model, which were transferred through contacts and resisted particle rotations (Iwashita and Oda 1998). Particle breakage was not considered here, because of relatively low pressures adopted in simulations. The following five main local material parameters were needed for discrete simulations: E_c (modulus of elasticity of grain contact) υ_c (Poisson's ratio of grain contact), μ (the inter-particle friction angle), β (rolling stiffness coefficient) and η (moment limit coefficient) which were calibrated with corresponding triaxial laboratory test results with Karlsruhe sand (Wu 1992) ($E_c = 30$ GPa, $\upsilon_c = 0.3$, $\mu = 18^{\circ}$, $\beta = 0.7$ and $\eta = 0.4$). In addition, the particle radius R, particle density ρ and damping parameters α were required ($\rho = 2{,}550$ kg/m^3 and $\alpha = 0.08$).

The plane DEM calculations were performed with a sand body of a height of $H = 200$ mm and length of $L = 400$ mm. Along the depth, the granular specimen was composed of one grain layer. The height of the retaining wall was assumed to be $h = 200$ mm. The vertical retaining wall and the bottom of the granular specimen were assumed to be stiff and rough.

A typical particle configuration in the residual state at $u/h = 0.15$ (u-horizontal displacement of the wall) with the distribution of single sphere rotations ω is presented in Fig. 1a–c (red colour denotes the sphere rotation $\omega > +30^{\circ}$ and blue the sphere rotation $\omega < -30^{\circ}$, dark grey is related to the sphere rotation in the range $5^{\circ} \leq \omega \leq 30^{\circ}$ and light grey to the range $-30^{\circ} \leq \omega \leq -5^{\circ}$, the positive rotation means the clockwise rotation). All grains rotating within the range $-5^{\circ} \leq \omega \leq 5^{\circ}$ are medium grey. Accepting such colour convention makes shear zones clearly observable (only particles within shear zones significantly rotate). The thickness of the main curved shear zone is at the residual state: $t_s \approx 50$ mm ($10 \times d_{50}$) for $d_{50} = 5$ mm, $t_s \approx 33$ mm ($16 \times d_{50}$) for $d_{50} = 2$ mm and $t_s \approx 20$ mm ($20 \times d_{50}$) for $d_{50} = 1.0$ mm. The layout of shear zones depends on d_{50}. For $d_{50} = 1.0$ mm it is similar as in experiments with $d_{50} = 0.5$ mm (Niedostatkiewicz et al. 2011).

The distribution of void ratio across the main curved shear zone is strongly non-uniform and also has its maximum along the centre line (Fig. 1d). The void ratio strongly varies along a shear zone.

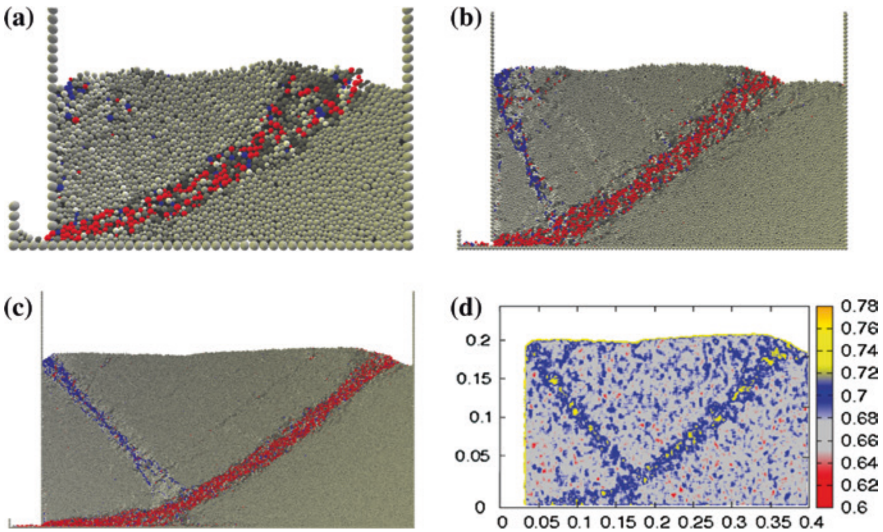

Fig. 1 Deformed granular body 0.2 × 0.4 m^2 with distribution of sphere rotation ('a'–'c') and void ratio ('d') for initially medium dense sand ($e_o = 0.62$) from DEM at residual state of $u/h = 0.15$: **a** $d_{50} = 5$ mm, **b** $d_{50} = 2$ mm, **c** and **d** $d_{50} = 1$ mm

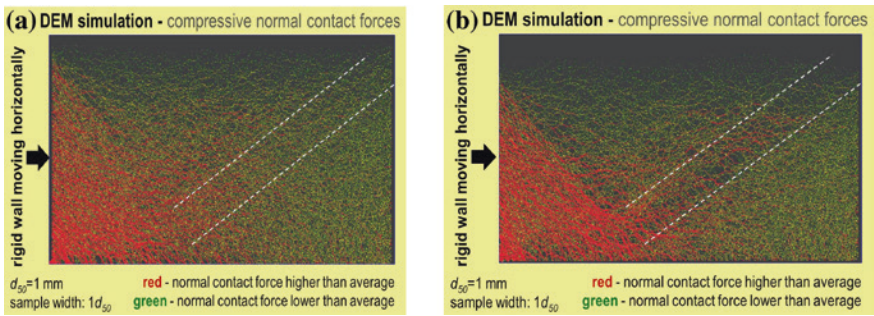

Fig. 2 Distribution of contact normal forces between spheres in entire granular specimen ($e_o = 0.62$, $d_{50} = 1$ mm) from DEM at: **a** $u/h = 0.02$ (without shear zone), and **b** $u/h = 0.15$ (full development of shear zone)

Figure 2 shows the two stages of the main shear zone evolution seen through the contact force network: (a) onset of shear localization and (b) shear zone fully developed. The location of the shear zone is indicated by the dashed lines. The 'force chains' bearing loads greater than average are marked red and those loaded below the average are marked green. The distribution of internal contact forces is non-uniform and continuously changes (Kozicki et al. 2013; Tordesillas et al. 2010). Force chains of heavily loaded grain contacts bear and transmit the compressive load on the entire granular system and are the predominant structure

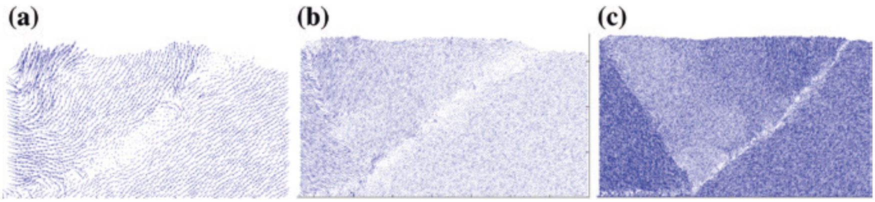

Fig. 3 DEM results ($e_o = 0.62$): formation of vortex structures in granular specimen at residual state of $u/h = 0.15$: **a** $d_{50} = 5$ mm, **b** $d_{50} = 2$ mm and **c** $d_{50} = 1.0$ mm

of internal forces at micro-scale. They continuously build up and collapse. The force chains are created mainly in the region between the wall, main and radial shear zone and along the main shear zone. The loads they transmit are the highest at the triangular region adjacent to the wall due to a great number of strong force chains (this region acts as a quasi-rigid body, Fig. 2). Inside the main curved shear zone at the residual state (Fig. 2b), the strongest force chains are approximately perpendicular to the shear zone line. The number of contacts decreases in a curved shear zone during wall translation due to sand dilatancy leading to a reduction of the number and stability of force chains.

Figure 3 presents spontaneous displacement changes within shear zones in the form of cells circulating as quasi-rigid bodies (so-called vortex structures) (Kozicki et al. 2013; Tordesillas et al. 2010). The plots in Fig. 3 were obtained by drawing the difference $\vec{V}_i - \vec{V}_{avr}$ between the displacement vector for each sphere and the average background translation corresponding to the homogeneous (affine) strain in the entire specimen ($\vec{V}_i$ represents the increment of sphere displacement during e.g. $n = 1{,}000$ iterations and $\vec{V}_{avr}$ is the average sphere displacement in the entire granular specimen for the same number of iterations). The vortex-like patterns are well recognized in the main curved shear zone, in particular, at the residual state for the highest mean grain diameter $d_{50} = 5$ mm. Several clockwise rotating vortices: 3 for $d_{50} = 5$ mm and 10 for $d_{50} = 1$ mm occur along the shear zone, having the diameter of about the shear zone width t_s. The distance between the vortices is variable (between t_s and $5 \times t_s$).

A link between force chains, vortex structures and void ratio changes in the region 70×100 mm^2 of the main curved shear zone at the residual state during the wall normalized displacement interval of $u/h = 0.01$ (from $u/h = 0.15$ up to $u/h = 0.16$) is demonstrated in Fig. 4 for the granular specimen built of $d_{50} = 5$ mm spheres. Two deformation stages are considered: (1) when the vortex exists at $u/h = 0.15$ (Fig. 4Aa) and (2) when the vortex does not exist at $u/h = 0.16$ (Fig. 4Ba). The force chain vanishes at $u/h = 0.15$ (Fig. 4Ba) and the new force chain is created at $u/h = 0.16$ (Fig. 4Bb). Small local dilatancy occurs close to a broken force chain (Fig. 4Ac–Ae) and small local contractancy takes place near a new force chain (Fig. 4Bc and Be). Thus, the occurrence and vanishing of vortex structures is related to the both force chain's creation and disappearance (Liu et al. 2012) and to the void ratio's decrease and increase

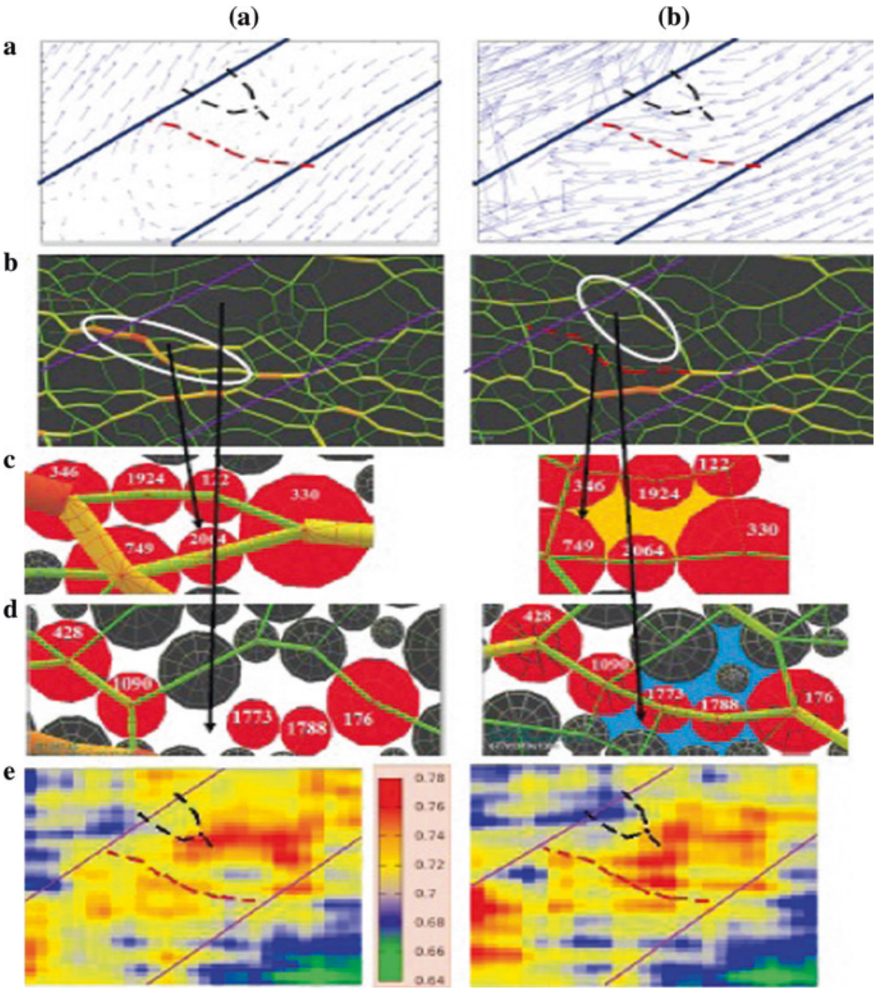

Fig. 4 DEM results ($e_o = 0.62$, $d_{50} = 5$ mm): evolution of micro-structures in main curved shear zone for normalized wall displacement at $u/h = 0.15$ (**a**) and $u/h = 0.16$ (**b**): (*solid lines* shear zone edges) (*a*) map of displacement fluctuations of Fig. 3a (*red dashed line* broken force chain, *black dashed line* new force chain), (*b*) geometry of force chains between spheres (*red dashed line* broken force chain), (*c*) and (*d*) zoom on geometry of force chains and spheres (*red spheres* build force chain, *yellow colour* between spheres denotes higher void ratio, *blue colour* between spheres denotes lower void ratio) and (*e*) map of void ratio

(Iwashita and Oda 1998). However, we have also observed that the occurrence and vanishing of vortices may correspond to the force chain softening and hardening only. The number of vortices increases with decreasing mean grain diameter and the distance between them increases with increasing mean grain diameter.

3 Conclusions

The discrete element method realistically simulates the experimental complex pattern of shear zones in the interior of initially medium dense sand. The results depend on the mean grain diameter.

The distribution of internal compressive contact forces is non-uniform due to a build-up and collapse of force chains. The number of contact forces continuously decreases in a granular specimen due to material dilatancy.

Vortex structures and local void ratio fluctuations spontaneously appear within the displacement field of shear zones and seem to have a periodically organized structure. The vortex diameter corresponds to the shear zone thickness. The vortices move as rigid bodies with small displacement fluctuations and insignificant rotations of single spheres.

The vanishing and appearing vortices may be connected not only with collapse and build-up of force chains, but also with their deformation. The collapse of force chains leads also to the formation of larger voids and their build-up to the formation of smaller voids.

References

Iwashita K, Oda M (1998) Rolling resistance at contacts in simulation of shear band development by DEM. ASCE J Eng Mech 124(3):285–292

Kozicki J, Donze FV (2008) A new open-source software developed for numerical simulations using discrete modelling methods. Comput Methods Appl Mech Eng 197:4429–4443

Kozicki J, Niedostatkiewicz M, Tejchman J, Mühlhaus HB (2013) Discrete modelling results of a direct shear test for granular materials versus FE results. Granular Matter 15(5):607–627

Liu X, Papon A, Mühlhaus HB (2012) Numerical study of structural evolution in shear band. Phil Mag 92(28–30):3501–3519

Niedostatkiewicz M, Leśniewska D, Tejchman J (2011) Experimental analysis of shear zone patterns in sand for earth pressure problems using particle image velocimetry. Strain 47(s2):218–231

Tordesillas A, Walker DM, Qun Lin Q (2010) Force cycles and force chains. Phys Rev E 81:011302

Wu W (1992) Hypoplastizität als mathematisches Modell zum mechanischen Verhalten granularer Stoffe. Ph.D. thesis, University of Karlsruhe, Karlsruhe

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