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Discrete element modelling study of force distribution in a 3D pile of spherical particles

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ABSTRACT

We present a numerical analysis of the transmission of contact forces in a granular pile comprising 50,000 frictional, coarse spherical particles. The goal of our study is to understand the microscopic origins of macroscopic behaviours, such as the pressure dip at the centre of the base of a conical pile. The particles are 8.2 mm in diameter with a standard deviation of 0.1 mm to avoid ordering effects. The effects of the pouring method, inter-particle sliding friction and rolling friction on the distribution of static stress are examined. The analysed microscopic variables are the distributions of the values and directions of the contact forces as well as the degree of mobilisation of contact friction. The vertical, radial and shear stress components are derived from the discrete contact forces. The analysed macroscopic variables are the distribution of the stress components, mobilisation of internal friction and inclination of the major principal stress to the vertical. The simulation results show that certain combinations of the examined factors lead to the formation of dome-shaped structures of maximum values of mean pressure as determined by the stress distribution inside the pile as well as at its base.

1. Introduction

Particles fall under gravity, similar to a liquid, in an apparently homogeneous stream and settle on a flat surface creating a pile. Under static equilibrium between the forces of gravity and friction, the assembly assumes a conical shape and behaves like a solid. Inside the deposit, the distribution of intergranular forces is far from homogeneous. Experiments on granular beddings sometimes reveal counterintuitive behaviour. One such behaviour is the pressure distribution under a conical sandpile. The location of maximum pressure at the base might be expected at the location having the greatest material height, that is, at the centre. However, experiments have revealed a local minimum at this point, as shown by Brockbank et al. [7]. They developed a method for measuring the pressure distribution in granular materials by observing the contact diameters of ball bearings on a rubber surface. A pressure dip was observed at the base of a pile of sand and small glass beads, whereas no dip was observed with large beads. McBridge [36] found the magnitude of this pressure drop to be approximately 40% of the hydrostatic pressure at the centre of a 2-m-high stockpile. A number of such studies have been performed; however, their results are contradictory, as reported by Vanel et al. [46], who explored the effect of the construction history of the sandpile on the stress profile at its base. An 'M'-shaped pressure dip was observed at the centre of the pile in heaps formed from a funnel. In the case of a more uniform 'rain' filling, the dip disappeared [18]. The most important difference between the various filling techniques was the amount of disorder in the contact orientations.

The M-shaped dip in the pressure distribution at the base of a stockpile can be attributed to the ability of granular solids to transmit static shear stress. Mechanisms of stress transmission leading to an 'M' dip at the centre of a stockpile have been the subject of intensive study over the past 25 years. In addition to analytical approaches [19,21,22,27,30,39], researchers have also used numerical approaches based on finite element modelling (FEM) [1,20] and discrete element modelling (DEM) for particles of different shapes, including spherical, ellipsoidal and convex polygons [5,29,31,37,41,48,49].

Analytical considerations allow specific cases of pile formation without a dip to be distinguished from cases with a clear 'M' dip in the bottom pressure [30,39]. A pressure minimum was observed when the piles were composed of particles with different sizes and when particles were segregated by size [31].

A pressure dip was also obtained in the FEM modelling of a pile. Hattamleh et al. [20] applied a multi-slip model to FEM code to investigate the stress dip phenomenon in a granular heap. They found that an initial slip orientation different from the classical Mohr–Coulomb solutions results in a peak in the stress. Ai et al. [1] obtained a similar finding using FEM modelling with a progressive mesh activation scheme, which indicated that the pressure dip is much higher for the Drucker–Prager plasticity model compared to the Mohr–Coulomb plasticity model.

A significant pressure dip under the apex of the pile was confirmed in 2D and 3D DEM simulations. The disappearance of the pressure dip in the case of a thicker filling stream observed experimentally by Vanell et al. [46] was noted also in DEM modelling [48]. Findings reported in

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the literature indicate that slight variation from a spherical particle shape or a change of friction (rolling or sliding) may have similar effects on the mechanical behaviour of a granular assembly. The repose angle of a pile composed of spheres determined in DEM simulations increased with an increase in both: the sliding and rolling friction [40,47]. The influence of the rolling friction on the repose angle, and of aspect ratio *AR* of ellipsoidal particles were found alike. Wensrich and Katterfeld [47] interpreted this similarity as a 'shapelike' behaviour of spherical particles introduced by rolling friction. Accuracy of DEM modelling of a pile behaviour, silo pressure and silo discharge increases when an effect of non-spherical shape of particles is accompanied by adequate values of coefficients of sliding and rolling friction [3,33,49]. DEM simulations indicated that an assembly of spherical particles produced erratic or relatively constant pressure distributions under the apex, compared to the more pronounced pressure dip produced by non-spherical particles [48,49]. These findings are consistent with the experimental results of Zuriguel et al. [50] indicating that non-spherical particles are oriented mostly horizontally, taking the most stable position with respect to gravity. This orientation influences the orientation of contacts and ultimately amplifies the pressure dip. Markauskas et al. [34] indicated that a pile of multi-spheres composed of at least 9 spheres produced an angle of repose similar to that produced by a pile composed of smooth ellipsoidal particles, whereas a lower number of sub-spheres gave a stronger interlocking effect and, as a result, a higher angle of repose.

The force chain evolution during loading depends on the single-particle properties and the initial structure of the packing [2]. Numerous contributions suggest that examination of the stress profile under a static granular pile may give greater insight into the effects of force chains and the history of their formation [44,46]. Experimental studies indicate that the pressure dip appears when the pile is poured from narrow source lifted steadily, with the outlet localized always slightly above the pile apex [27,46]. This finding was corroborated in DEM simulations [48]. A mechanism of an increase of the pressure dip with an increase in *AR* may be similar to an effect of an increase of a repose angle. A systematic study of the impact of the sliding and rolling friction on the repose angle of a pile of spherical particles provided important findings [40,47]. It seems to be interesting to verify if sliding and rolling friction, which introduce 'shapelike' behaviour of spherical particles, may have similar effect on the pressure dip. The force distribution between particles in a 2D granular pile was the most frequently studied, while results regarding 3D piles are scarce.

Therefore, the objective of this study was to determine the pressure dip under a 3D pile in the least evident case of a pile composed of the coarse-grained spherical particles and to investigate the effect of sliding and rolling friction. We analysed the pressure distribution under a pile as an effect of the evolution of the stress components inside the pile during its formation.

2. Setup of DEM simulations

The DEM simulations were performed with an assembly of 50,000 spherical particles. The particles were 8.2 mm in diameter with a standard deviation of 0.1 mm. The diameters of the spheres were normally distributed from 8 mm to 8.4 mm. To verify the effect of the range of particle size distribution on results of DEM simulations, the size distribution was increased four times with appropriate increase of the standard deviation (Table 1). Based on the work of Mindlin and Deresiewicz [12], the Hertz–Mindlin theory of elastic frictional collisions between particles (particle–wall) was used for the simulations. Visco-elastic damping was applied in the contact model, as proposed by Tsuji et al. [45], with the assumption that the coefficient of restitution is constant for a given set of particle properties. The material parameters of the particles were taken as follows, reflecting typical properties for agricultural coarse seeds: particle solid density $\rho = 1257$ kg m^{-3}, Young's modulus $E = 526$ MPa, Poisson's ratio $\nu = 0.26$ and coefficient of restitution $e = 0.6$ [23]. Numerical experiments were conducted to explore the effects of inter-particle sliding and rolling friction, and filling method conditions on the force distribution inside a pile. The coefficient of particle–particle friction μ_{p-p} in a range from 0 to 1.5 and the coefficient of rolling friction m_r in a range from 0 to 0.3 (Table 1) were adopted to be comparable to values applied in similar studies for spherical particles to produce a pile with a realistic angle of repose [40,47–49]. Particles were generated in a filling device and poured through an orifice of radius $R_o = 0.02$, 0.04 and 0.08 m (see Fig. 1). To reduce the kinetic energy effect of the falling particles, the filling device was slowly lifted to maintain the distance between the uppermost particle of the deposit and the orifice to 4–8 particle diameters. To examine the effect of the kinetic energy of the falling particles, a pile was generated by pouring particles from a source located 2 m above the base plate. The deposit was equilibrated until the total kinetic energy in the entire system fell below 10^{-5} J. The time integration was carried out using semi-implicit Euler method with the step 3.5 10^{-6} s, i.e. 10% of Rayleigh time step [24]. The EDEM software package [11] was used for the numerical simulations.

Table 1
DEM simulations parameters.

Parameter	Symbol	Value
Particle:		
Mean particle radius [mm]	r_p	4.1
Standard dev. of particle radius [mm]	r_{sd}	0.05; 0.2
Particle radius range [mm]		4.0–4.2; 3.7–4.5
Young's modulus [MPa]	E	526
Poisson's ratio [−]	ν	0.26
Restitution coefficient [−]	e	0.6
Particle-base friction coefficient [−]	μ_{p-w}	0.35
Particle-particle friction coefficient [−]	μ_{p-p}	0–1.5
Rolling friction coefficient [−]	m_r	0–0.1; 0.3
Particle solid density [kg·m^{-3}]	ρ	1257
Particle number [−]	N	50,000
Time step [s]	Δt	$3.5\cdot10^{-6}$
Simulation setup:		
Bottom plate Young's modulus [MPa]	E	$2\cdot10^5$
Bottom plate Poisson's ratio [−]	ν	0.3
Filling height [m]	H	0–0.065; 2
Filling orifice radius [m]	R_o	0.02; 0.04; 0.08

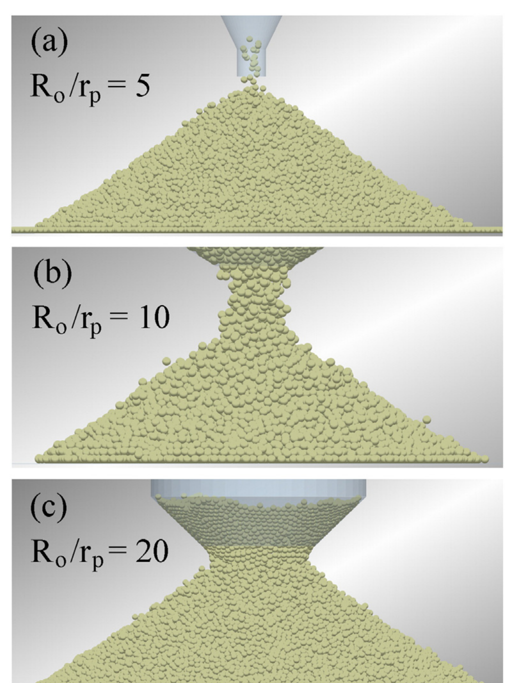

Fig. 1. Scheme of filling procedure.