University of Dundee

Proceedings of the 18th UK Travelling Workshop

Ciantia, Matteo; Previtali, Marco; Bolton, Malcolm

DOI:

[10.20933/100001228](https://doi.org/10.20933/100001228)

[10.20933/100001228](https://doi.org/10.20933/100001228)

Publication date:

2021

Document Version

Publisher's PDF, also known as Version of record

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):

Ciantia, M., Previtali, M., & Bolton, M. (Eds.) (2021). *Proceedings of the 18th UK Travelling Workshop: GeoMechanics: from Micro to Macro (GM3), Dundee, 2021*. (GM3 Travelling Workshop Proceedings; No. 1). University of Dundee. <https://doi.org/10.20933/100001228>, <https://doi.org/10.20933/100001228>

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2D Image-based calibration of rolling resistance in 3D discrete element models of sand

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Key words: *rolling resistance; DEM; Image analyses; Particle Shape, Calibration*

Abstract

Contact rolling resistance is the most widely used method to incorporate particle shape effects in the discrete element method (DEM). The main reason for this is that such approach allows for using spherical particles hence offering substantial computational benefits compared to non-spherical DEM models. This paper shows how rolling resistance parameters for 3D DEM models can be easily calibrated with 2D sand grain images.

1. Introduction

In recent years, the Discrete Element Method (DEM) has been used to bridge the gap in knowledge between micro and macroscopic soil behaviour. One of the main drawbacks of DEM, preventing more regular industrial application, is constituted by the significant simulation time for large scale problems. While spherical particles are the most computationally efficient, they are very unlike most grain shapes. In this context, different approaches have been developed to include particle shape in the model, such as: clumps and aggregates of spheres (Katagiri, 2018), polyhedrons (Boon *et al.*, 2012), superquadrics (Williams and Pentland, 1992) or level sets (Jerves *et al.*, 2016). Increased realism has the advantage of bringing the shear strength and dilatancy to more physically reasonable values (Rothenburg and Bathurst, 1992), but increases the computational time with respect to sphere-based models (Irazábal *et al.*, 2017). (Iwashita and Oda, 1998) introduced the rolling resistance model, i.e. rolling resistance, at the particle contacts, as an alternative that maintained the efficiency of sphere-based contact detection. This was based on Bardet, (1994) who observed that particle rotation concentrates within shear bands, and that limiting rotation in DEM increased macro-scale friction and dilatancy. The drawback of this approach is that new micro contact parameters are introduced, without any other calibration means that observation of their effect on mesoscale response, a procedure that may be time consuming and difficult (Cheng *et al.* 2017). Rorato *et al.*, (2021) proposed a technique to calibrate this model through 2D image analysis, which is quick and inexpensive. Herein, the basics of this approach are explained and applied to characterize a sand from the river Ticino. Successively, the model is evaluated by comparing numerical pipeline-soil interaction simulations with experimental physical models performed with the same sand. (Di Prisco and Galli, 2006).

2. Method

The particle shape is characterized through the degree of true sphericity ψ (Wadell, 1932), defined as the ratio between the particle surface area and the surface area of a sphere of equivalent volume. 3D image analysis techniques may be used for this measurement, but access to the requisite equipment (i.e. μ -CT) is often limited. On the other hand, 2D images are very easily obtained. For this reason, particle geometry is herein characterized using a 2D proxy measure of sphericity, the perimeter sphericity S_p ;

defined as the ratio between the perimeter of the circle with area equivalent to the projected by the particle within the image, assuming the grain image is taken on the plane of maximum particle stability. Following (Rorato *et al.*, 2019), these two descriptors are characterized by a linear relationship (I), which appears to be constant for different sands.

$$\psi = 1.075(S_p) - 0.067 \quad (1)$$

The rolling friction μ_r is then characterized using an exponential function:

$$\mu_r = A(\psi)^{-b} \quad (2)$$

Where A and b are two fitting parameters. These parameters were calibrated by (Rorato *et al.*, 2021) using a experimental database of particle rotation within shear bands (Rorato *et al.*, 2020). The same calibration appeared to work for all tested sands (Hostun, Caicos, Ottawa, Ticino).

Figure 1: Digitalization of Ticino sand grains and true sphericity distribution for the 2500 grains scanned

Figure 2: Comparison of experimental and numerical triaxial test data

Ticino sand grains were digitalized using a standard office scanner. After converting the image from RGB (red, green, and blue) to HSV (hue, saturation, and value), a threshold filter based on hue and saturation is used to separate the grains from the background. Finally, overlapping grains are separated using a watershed algorithm (Dougherty *et al.*, 2019). Figure 1 shows the digitalization procedure described above and reports the ψ distribution for Ticino sand used to determine rolling friction μ_r for the DEM model. Each grain is assigned a μ_r , thus mapping the experimental ψ distribution into one of rolling friction. Figure 2 compares experimental and DEM triaxial compression of Ticino sand. For the DEM two cases were considered; a cylindrical sample with rigid walls and a cubic model confined by periodic boundary conditions. The contact parameters are taken from Rorato *et al.*, (2021). The cylindrical DEM model, allowing for shear band formation, captures the experiment better whilst the

periodic boundary REV shows some deviation from the result. Such response is reasonable as shear banding was observed in the laboratory experiments but is not possible in the periodic cell.

3. Numerical model for soil pipe-interaction

The calibrated DEM model is now used to examine soil pipe interaction behaviour. The experimental physical models, also performed using Ticino sand, are taken from Di Prisco and Galli, (2006). To prepare the numerical model the efficient approach by Ciantia *et al.*, (2018) is used. A cubic REV is equilibrated at the target porosity and replicated to fill the domain. To attain plane strain conditions, periodic boundaries are kept in one direction. The DEM particles at the edges of the sample are fixed to impose the fixed lateral boundary conditions (Figure 3). Contact forces are scaled to replicate gravity conditions after a cylinder of diameter D is buried at depth z through a wished-in-place approach. Vertical, horizontal, and inclined pull-out tests are performed at different embedment depths. Figure 4 reports the horizontal capacity of the cylinder when displaced horizontally whilst maintaining the vertical load constant. A snapshot representing particle rotation is also reported in the figure. The good match between the experimental results and the DEM numerical model suggests that the image-based calibration procedure is effective also for model scale simulations, particularly where shear band and strain localizations are expected.

Figure 3: on the left, stress state within the domain, on the right, snapshot of the model.

Figure 4: Horizontal force - displacement curve for horizontal pull tests for different embedment depths and snapshot of particle rotational velocity.

4. Conclusions

The approach proposed by (Rorato *et al.*, 2021), whereby particle shape is incorporated at the contact scale by means of an image calibrated rolling resistance parameter has shown to be effective in

capturing the experimental behaviour of an angular sand such as Ticino sand. It is noted that the calibration of the model was performed by matching experimental triaxial compression tests, while the pipe-soil interaction simulations were performed without any further tuning of the contact parameters.

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