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Quantifying influence of particle morphology during shallow indentation of a granular ensemble

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Abstract. This study investigates the effect of particle shape on mechanical response of granular materials under shallow indentation. Two model materials at the same size but with vastly varying morphologies were used here. The experiments were performed inside an Xray CT system. A Morse theory based segmentation algorithm was employed in the analysis. The kinematics was studied at multiple length scales. The extent and features of the deformation zone, the micromechanical parameters such as coordination number, and the overall load characteristics were all functions of the individual particle morphology.

1 Introduction

Indentation is an important experimental technique with widespread applications in non destructive testing of mechanical properties of a wide array of materials. Material properties such as hardness, elastic modulus, yield strength, fracture toughness in solids are all correlated to the indentation or hardness magnitude [1]. The mechanics of indentation has a strong theoretical foundation in plasticity theory. Flat punch indentation has also provided the most important theoretical foundation for design of shallow footings in infrastructure. Model tests in centrifuge, field tests, and physical model tests on footings in granular materials have played a key role in developing design strategies of shallow foundations under a variety of load and soil conditions [2, 3]. Typically, foundation design focuses on determining the ultimate load capacity and the associated settlement of the footing, often without critical analysis of the deformation of the soils. An understanding of the deformation profile of the underlying soil is a crucial input for limit analysis based solutions. Experiments in plane strain and in a calibration chamber have all contributed to increased understanding of the mechanics of shallow indentation on geomaterials [4, 5]. The deformation of a granular geomaterial ensemble (such as sands, silts, clays etc) is well recognized as a function of the individual particle morphology, size distribution, and constituent mineralogy. In effect, the packing density, permeability, shear strength and the deformation response to any external loads of a granular ensemble are all functions of the individual particle morphology [6, 7]. Given the recent advances in X-ray computed tomography (XRCT) and image segmentation algorithms have contributed in no small measure to a multiple length scale understanding of the granular material response. High resolution measurements of complex particle rearrangements, localization and deformation under complex boundary conditions have all been possible due to the advancements in XRCT [8, 9]. Segmentation of CT images, is a critical step that enables identification of individual objects in an image and provides a unique identification for all the features of the CT image. This crucial step in the image analysis is necessary for understanding the particle kinematics during deformation processes. Conventional algorithms used for segmentation of granular materials such as watershed-based algorithm are sufficient for segmentation of rounded and convex shaped particles. However, these watershed based algorithm significantly under-segment or over-segment particles that are flaky and angular [10].

In this paper, we present the analysis of a series of experiments on a model shallow footing founded on glass ballotini and angular sand conducted inside a XRCT set up and the images were segmented using a robust Morse theory-based framework. Indentation tests or shallow footings tests were conducted on two model granular materials — spherical glass ballotini and angular sand particles. The scans were performed at 3 different depths of penetration (ensuring that the indentation was shallow). The images obtained from these CT scans were analysed through an image processing pipeline. The segmentation, and digital volume correlation (DVC) were used to track the labeled particles in the successive loading stages. The influence of particle shape was examined at both the particle or micro-scale and the ensemble or macro-scale.

2 Material and analysis

2.1 Materials

Two samples were prepared using glass ballotini and sand with a mean diameter of 0.60 mm. The sample was prepared within an acrylic cylinder measuring 38 mm in diameter and 70 mm in height. A schematic diagram of the

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test setup used inside the XRCT apparatus is provided in Figure 1(a). An aluminum indenter of 5 mm diameter was securely fixed at one end of the apparatus, while a displacement-controlled stepper motor with a load capacity of 2000 N was used to move the sample toward the indenter. During the experiment, the sample was rotated from 0^0 to 360^0 in 2^0 increments, and scans were captured at a high resolution of 44 μm. Two loading stages were employed with interrupted scanning after every load stage.

2.2 Analysis procedure

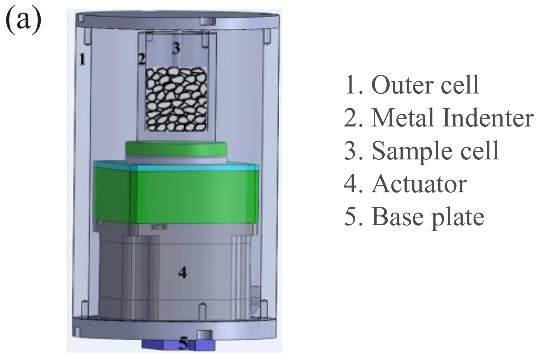
Once a stack of images is obtained in the XRCT experiments, two key image analysis steps are required to gather information on the kinematics of the granular ensemble during indentation. The first step is pre-processing the reconstructed images, as low contrast, noise, and artifacts in CT scans can misrepresent the true object geometry. To mitigate these artifacts, appropriate contrast adjustments and filtering were applied before performing image binarization in MATLAB. The second critical step is the process of segmentation of particles from the 3D image stack. The choice of a segmentation algorithm used depend on several factors, important among which are computational efficiency, and ability to segment a range of complex particle shapes.

The series of indentation experiments performed in this research programme contained approximately half a million sand / glass ballotini particles. Given the scale of the dataset that was generated, a robust and accurate code is required to handle such large volumes of data effectively. A Morse theory based segmentation scheme - MorseGram [10] was used in the present work. This method utilizes the topological characteristics of an object, to generate a geometric representation of the particles. Segmentation of the particles and voids through MorseGram was found to be effective in the experiments, enabling the identification of angular and elongated particles—features that are typically difficult to distinguish using conventional methods such as the watershed algorithm. In addition to boundary extraction, MorseGram enables efficient computation of geometric features and supports analysis of particle and contact orientation. It also provides a specific identification, key geometric properties such as the particle surface area, volume, and equivalent radius, along with neighbor information. MorseGram vis [11] also provides insights into the coordination number histogram, eigenvalues, and their directions, making it well-suited for micro-mechanical studies.

3 Results and discussion

3.1 Load displacement behavior

Figure 1(b) presents the load displacement response for sand and glass ballotini samples. The cylindrical rod is inserted into the granular ensemble, i.e. increasing the depth of penetration in two stages and scanning the specimen after every stage of loading. The overburden pressure slowly increases as the indenter traverses through the three stages



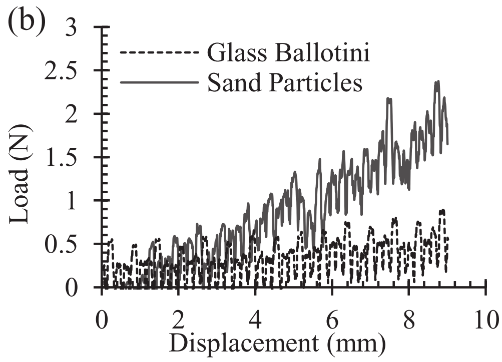


Figure 1. (a) A schematic diagram of indentation test setup, and (b) average load displacement curve for the glass ballotini and sand specimens.

of shallow indentation. The maximum force applied to the sample is nearly 0.8 N in case of ballotini ensemble, whereas angular sands show about 3 times higher loads i.e. 2.4 N load at a depth of 9 mm. The angular sand particles show this increased resistance to the movement of the footing due to the significantly higher friction between the sand particles.

3.2 Segmentation accuracy and displacement fields

The labeling of individual particles in the ensemble was necessary in order to obtain the kinematics of the particles. Figure 2 presents segmented images of ballotini and sand particles. MorseGram offers a unified data structure that stores both segmentation and contact information, serving as an efficient tool for visualizing segmentation and connectivity networks as shown in Figure 2(b,d). It utilizes a topological persistence-based approach that eliminates both geometric and topological noise, leading to accurate and reliable segmentation. The kinematics of the indentation process was tracked using the Software for Practical Analysis of Materials (SPAM) [12]. This code requires both the deformed and undeformed volumes of the ensemble, along with a labeled image of the undeformed volume. The Figure 3 illustrates the displacement fields obtained

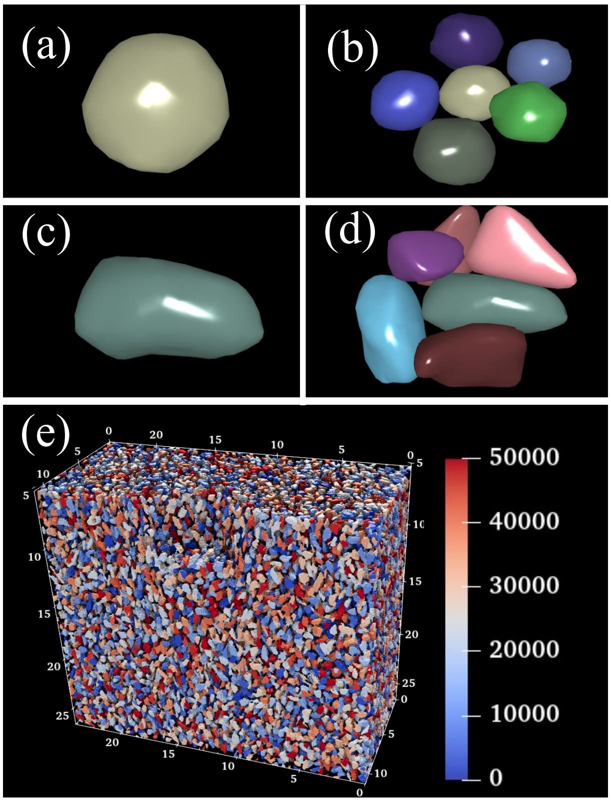


Figure 2. (a)&(b) Segmented glass ballotini particle with its neighboring particles, (c)&(d) segmented angular sand particle with its neighbors and (e) half sectional view of the sand ensemble segmented by MorseGram where the color represents the IDs of different particles.

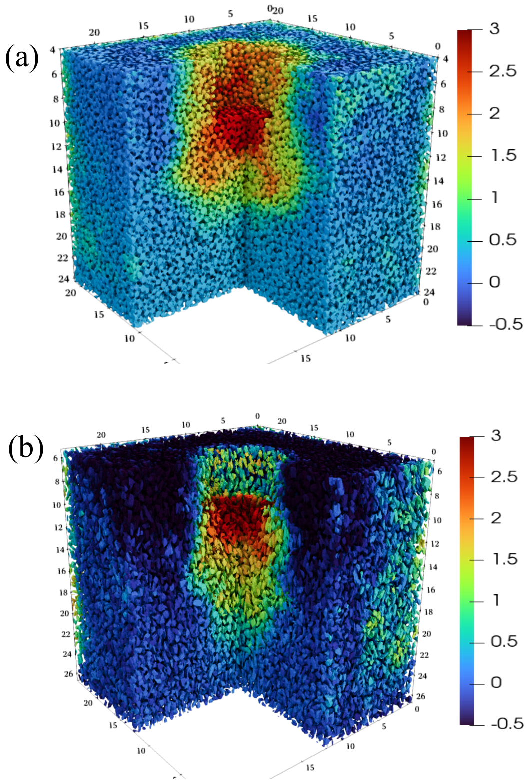


Figure 3. Contour map of vertical displacement field for (a) glass ballotini and (b) sand particles ensemble when indenter moves from 6 mm to 9 mm depth.

from glass ballotini and sand particles. The highest deformation occurs directly beneath the indenter tip, with displacement fields gradually diminishing radially outward from the indenter axis.

Positive displacement field values indicate regions of contraction, while negative values correspond to dilation. The deformation is primarily concentrated in a narrow zone beneath the tip of the indenter. During each loading stage, the indenter was displaced along the vertical axis by 3 mm, equivalent to 5 times the particle's diameter. Notably, a small region directly beneath the indenter exhibits displacement values nearly identical to those of the indenter itself. This conical region, is usually referred to as the dead zone, behaves as an extension of the indenter in subsequent loading stages. The displacement field transitions smoothly, decreasing progressively radially outward.

In the case of the ensemble with glass ballotini, the zone of deformation is confined to a narrow region, with nearly zero displacement observed near the boundaries. The ballotini also rearrange under loading, and the region of deformation extends to 12 times the particle's diameter in the direction of the indentation. In contrast, angular particles show much larger tendencies of interlocking. It is interesting to note that in case of the angular sand ensemble, the particles surrounding the region of densification region show negative displacements, indicating movement in the direction opposite to that of the indenter. Consequently, the influence zone is larger for irregular particles when compared to glass ballotini (around 22 times the diameter of the particle).

3.3 Coordination number and packing fraction

The sand sample has a packing fraction of 0.52, whereas the ballotini particles achieve a denser packing of 0.62. The angularity of the particles hinders the close packing, resulting in a lower initial packing fraction. The MorseGram tool directly provides particle ids for determination of coordination number. Figure 4 presents a contour map of coordination number for a region close to the indenter. A half-sectional view of the inset is shown when indenter tip positioned at a depth of 6 mm and 9 mm. As the indenter advanced, the particles surrounding the indenter contract, resulting in an increase in the number of neighboring particles. This is evident in Figure 4(b), where there is a noticeable reduction in the number of dark-colored particles—indicating low coordination number as compared to Figure 4(a). The ballotini sample has an average coordination number of 6.3, while the sand particles have an average coordination number of 3.8. This difference arises because glass ballotini particles, with their smooth edges, facilitate the formation of many more contact points per particle. In contrast, angular particles offer fewer contact points, in effect a lower coordination number.

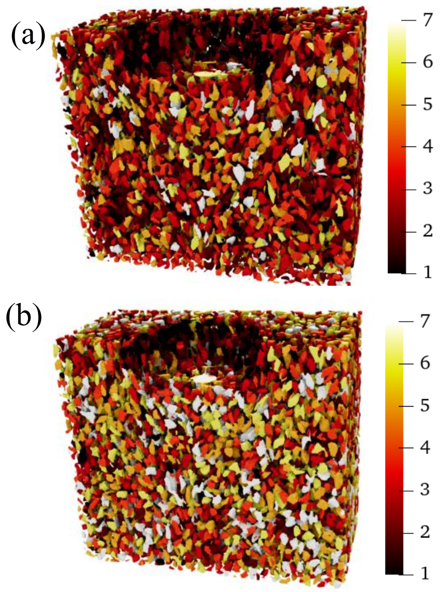


Figure 4. A half sectional view of coordination number distribution in sand ensemble when indenter was located at a depth of (a) 6 mm and (b) 9 mm. The coordination number increases when color transitions from dark to white band.

Though coordination number and packing fraction of the ballotini sample are higher than those of the sand, the load-displacement curve shows less stiffness in the ballotini ensemble (Figure 1). This is due to the shape of the particles and their contacts. The contacts in the spherical glass ballotini are point contacts, which are less effective in carrying localized force from the indenter. On the other hand, sand particles have angular shapes that facilitate particle interlocking and enhance resistance to the localized load.

These results provide a direct measure of the deformation underneath a shallow indenter, as function of particle morphology. The regions of high velocity gradients, coordination number, dead zone and high fidelity measurements of the deformation at the particle scale. These results are a first step towards a multiscale measure of the indentation problem in granular media.

4 Summary

The MorseGram segmentation algorithm is efficient in capturing complex particle morphologies when compared to traditional watershed algorithm. The kinematics at all length scales is a function of the morphology of particles. A dead zone of particles is present at the tip of the indenter. Deformation zone size and patterns, coordination number, and the load during indentation are all dependent on the particle morphology.

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