Review History for "X-ray tomography analysis of particle morphology influence on granular deformation processes"

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Summary

This paper was sent to two reviewers: one anonymous reviewer (Reviewer A) and Dong Wang (Reviewer B). The reviewers remained anonymous during the entire review process. After the reviewing process was complete, Reviewer B agreed to disclose their identity. The paper went through a single round of review. In this Review Round, all reviewers provided a series of comments for the authors. Both Reviewers recommended that revisions were required. After the response was received, the managing Editor decided to accept the manuscript for publication.

Review Round 1

Reviewer A

The authors study the quasistatic loading of oblate ellipsoidal particles in triaxial cell for three different aspect ratios and two surface roughness (yielding different interparticle frictions). They use in-operando x-ray tomography to measure the displacement and rotational fields. The force loading of the triaxial cell is also measured. The manuscript contains snapshoot figures of the measured displacement and rotational fields at peak stress and steady state as well as the probability density function of the incremental displacement and particle rotation at the final loading stage. Processing the data is used to calculate the evolution of the volumetric and deviatoric strains during the loading process.

The manuscript presents the capability of the authors to execute such measurements and provide some interesting data.

I have the following questions and comments:

1. It is clear that the authors had to choose a small number of different particle shapes to perform these demanding set of experiments, but can author motivate their choice to use oblate particles rather than prolate particles? Is it just due to availability?
2. The authors present the degree of bulk anisotropy of particle orientation at the beginning of the process but indicate that its evolution "goes behind the scope of this study", which is not clear to me why as it seems that all the data is already available to them. Can the authors explain what the challenge is in obtaining its evolution during the process.

3. The authors claim in section 2.2 Image analysis that "A novel approach is implemented" but the references given are not recent and no details of the noval approach are given. It will help the reader if the authors can explain what is novel in their approach.
4. Most of the result obtained are intuitive, however in figure 1a it depicted that the response of the particles with the largest aspect ratio, bound the depicted responses from above and below, rough (dark blue) and smooth (light blue), respectively. This is surprising and I authors should discuss this result.
5. Finally, it seems there is a small typo with the aspect ratio of the particles where 3.4mm/2.2mm=1.55 not 1.50 as indicated in Table 1.

In summary, the manuscript is clear, easy to read and demonstrate experimental capability and shows interesting results. Addressing my four questions/comments above will further improve that manuscript which I then recommend for publication.

Reviewer B (Dong Wang)

The manuscript entitled "An x-ray tomography investigation of the effects of particle morphology on the deformation process of granular materials" presents studies on how microscopic particle shape and friction impact the bulk deformation of the materials in three dimensions. Ellipsoids with different aspect ratio and friction are packed and tested in a triaxial compression setup. X-ray scan is employed to track particle dynamics throughout compression tests. The authors show that particles with mild anisotropy and high friction promotes large dilatancy due to competition between particle rotation and particle inter-locking. I will support the publication of the manuscript in Open Geomechanics if the following concerns are addressed.

Throughout the manuscript, the setup was mentioned a few times to explain observed results. However, I find it difficult to relate without a sketch of the setup, and a reference to a Ph.D. thesis could turn out to be a difficult search. Therefore, I suggest the authors to include a sketch of the setup as one of figures in the manuscript.

1. How big are the errors on inter-particle friction angle measurements and how many samples are tested?
2. Why did stick-slip events only occur for the medium-rough particles in Fig. 1(a)? I think the authors should run another test to confirm this is indeed caused by particle properties, not just an experiment error or fluctuation.
3. Lines 442-443 state "two triangular regions", which, however, are not clear to my eyes. Maybe highlighting those regions will be helpful.
4. It will be helpful to mark the locations corresponding to peak stresses in Fig. 1(a), like shown in Fig. 6, 9, and 10.
5. It may also be helpful to highlight in Figs. 5 and 7 the shear band regions determined from deviatoric strain.
6. This is a minor point. But in Fig. 6, I cannot tell the difference for the PDF's between rough and smooth curves for round particles in panel (b), yet the mean values at the end of curves in panel (a) are quite distinguishable. I don't understand why. As a comparison, I can tell the difference for the PDF's between rough and smooth curves for flat particles in panel (b), but not the mean values in panel (a).
7. Since the authors used the minor axis to determine particle rotation, rotation around the minor axis is not accessible (I think the authors noted this point as well). Is there any estimate on how much rotation around the minor axis is compared to rotations reported in the manuscript? If not, it's almost impossible to interpret results concerning particle rotation kinematics. I would imagine this quantity becomes more prominent in the round particle case, where authors have reported interesting behaviors.

Author Response

We appreciate the reviewers for taking the time to review our manuscript and provide helpful feedback. Their suggestions have given us the chance to improve our work, and we have made the necessary revisions accordingly. We believe that these changes have strengthened the manuscript, below is our detailed response to each comment.

Reviewer A

1. *It is clear that the authors had to choose a small number of different particle shapes to perform these demanding set of experiments, but can author motivate their choice to use oblate particles rather than prolate particles? Is it just due to availability?*

   Thank you for your comment. The decision to use oblate particles instead of prolate particles is based on two main reasons. First, flat particles are more commonly found in geological deposits than elongated ones due to natural deposition processes. Second, the alignment behavior differs between these two types of ellipsoids: while prolate particles align more easily during flow processes, such as granular flows or silo discharges, oblate particles promote alignment during deposition, see for example the work of Guillard et al. [2017] and Pinzón et al. [2023]. This results in inherently anisotropic deposits, replicating the geological characteristics of bedding planes. In contrast, elongated particles do not align during deposition, making it more challenging to achieve an initial alignment.

2. *The authors present the degree of bulk anisotropy of particle orientation at the beginning of the process but indicate that its evolution "goes behind the scope of this study", which is not clear to me why as it seems that all the data is already available to them. Can the authors explain what the challenge is in obtaining its evolution during the process.*

   Thank you for your comment. The fabric data is indeed available and was measured as part of the broader project underlying this study. Its response is non-monotonic and sometimes counterintuitive, requiring an extensive analysis spanning several pages. To address this comprehensively, a separate article—currently under review—has been prepared to examine the interaction between morphology and fabric development. This article delves into the evolution of inter-particle contacts and how their development contributes to explaining the material's shear strength. For reference, we have attached a copy of the complementary article to this response.

   To clarify this point and highlight the forthcoming article, we have revised the manuscript as follows:

   "The evolution of particle anisotropy and fabric, in general, falls outside the scope of this study and is addressed in an upcoming complementary article. However, noticeable differences in the initial values of ζ_P in Table 1 indicate significant variations in the internal arrangement of particles , influenced by their shape and friction angle, even before the application of the external load."

3. *The authors claim in section 2.2 Image analysis that "A novel approach is implemented" but the references given are not recent and no details of the novel approach are given. It will help the reader if the authors can explain what is novel in their approach.*

   While the image processing tools themselves are not novel, the key contribution of this study lies in the ability to track **every** individual grain throughout the experiment. To the best of the authors' knowledge, this is the **first** study to successfully measure the kinematics of **all** grains at each strain increment. To clarify this point, the manuscript has been revised as follows:

   "A novel approach is implemented to track 100% of the particles throughout each experiment, marking the first time that all individual grains are successfully followed at every strain increment. This is achieved using the iterative algorithm developed by Tudisco et al. [2017] in the "Discrete DVC" mode of Hall et al. [2010]."

4. *Most of the result obtained are intuitive, however in figure 1a it depicted that the response of the particles with the largest aspect ratio, bound the depicted responses from above and below, rough (dark blue) and smooth (light blue), respectively. This is surprising and authors should discuss this result.*

   Indeed the macroscopic q/p response of the flat particles bounds the response of all the other specimens when the inter-particle friction is changed. This can be explained by the value of initial anisotropy (ζ_P), where particle shape plays a significant role in determining the arrangement of the initial microstructure. It has been found that ζ_P can be used to estimate the macroscopic shear strength response when comparing different specimens. This relationship between shear strength and fabric is explored and thoroughly examined in the aforementioned separate article.

5. *Finally, it seems there is a small typo with the aspect ratio of the particles where 3.4mm/2.2mm=1.55 not 1.50 as indicated in Table 1.*

   Thank you for your comment. Indeed, there was a typo in Table 1, which has now been corrected.

Reviewer B

1. *Throughout the manuscript, the setup was mentioned a few times to explain observed results. However, I find it difficult to relate without a sketch of the setup, and a reference to a Ph.D. thesis could turn out to be a difficult search. Therefore, I suggest the authors to include a sketch of the setup as one of figures in the manuscript.*

We thank the reviewers for this comment. The sketch of the setup has been added to the manuscript as Figure 1.

2. *How big are the errors on inter-particle friction angle measurements and how many samples are tested?*

   For each combination of shape and surface conditions, 11 pairs of particles were tested to determine their friction angle under two distinct normal loads (4.5 N and 9 N). The mean values and the observed error, which ranges from 0.92° to 2.26° across the samples, have now been included in Table 1.

3. *Why did stick-slip events only occur for the medium-rough particles in Fig. 1(a)? I think the authors should run another test to confirm this is indeed caused by particle properties, not just an experiment error or fluctuation.*

   The stick-slip event observed exclusively in the medium-rough specimen results from the interaction between the base plate of the experimental setup and the piston, rather than the particle properties. To verify this, an additional triaxial compression experiment was conducted outside the X-ray tomography cabin with a different base plate, which exhibited a similar macroscopic response without the stick-slip events.

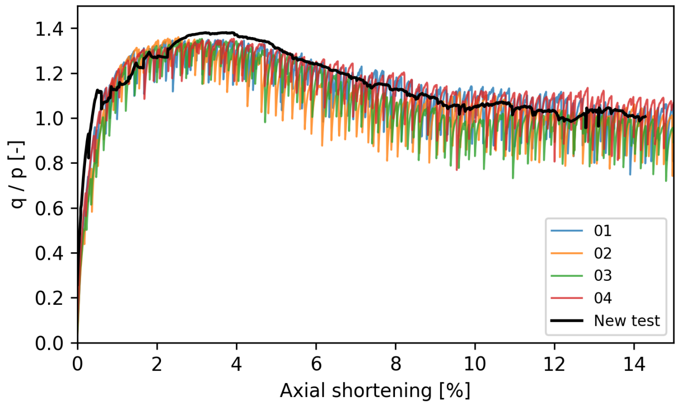

Figure 1: Macroscopic response of the medium-rough specimen. Colour-coded curves correspond to the original tests. Black curve correspond to the additional test performed with a new base plase and using the same particles and sample preparation protocols.

   We have revised the manuscript to clarify this point as follows:

   "Additionally, the greater variability observed in the medium-rough specimen is due to a stick-slip interaction between the base plate of the experimental setup and the piston, rather than the material's actual response. To confirm this, an additional triaxial compression experiment is conducted outside the X-ray tomography cabin using a different base plate, showing a similar macroscopic response without the stick-slip behavior."

   Additionally, the caption of the figure is modified as well as:

   "The increased variability observed in the medium-rough specimen is due to a stick-slip interaction between the base plate and the piston, rather than the material response. An additional experiment with a different base plate confirmed a similar macroscopic response without stick-slip behavior."

4. *Lines 442-443 state "two triangular regions", which, however, are not clear to my eyes. Maybe highlighting those regions will be helpful.*

   Indeed, the triangular regions are not clearly visible in the selected increment A, which may lead to confusion. To ensure clarity and consistency in the manuscript, we have removed this reference from the text.

5. *It will be helpful to mark the locations corresponding to peak stresses in Fig. 1(a), like shown in Fig. 6, 9, and 10.*

   We have marked the location of the peak stresses in Fig. 2(a).

6. *It may also be helpful to highlight in Figs. 5 and 7 the shear band regions determined from deviatoric strain.*

   We sincerely appreciate the reviewer's comment. We believe that directly highlighting the shear band region on top of the figures may over populate them, potentially hindering clarity and visualization by adding excessive details. To maintain readability, we prefer to keep the figures as they are, allowing the presence of discontinuities on the rotation and displacement fields to naturally suggest the location of the shear band in each measurement.

7. *This is a minor point. But in Fig. 6, I cannot tell the difference for the PDF's between rough and smooth curves for round particles in panel (b), yet the mean values at the end of curves in panel (a) are quite distinguishable. I don't understand why. As a comparison, I can tell the difference for the PDF's between rough and smooth curves for flat particles in panel (b), but not the mean values in panel (a).*

   Although the two distributions appear visually similar, their statistical properties reveal key differences. The rotation of rough round particles exhibits a higher mean than that of smooth round particles, and its distribution has a larger standard deviation (4.69° compared to 3.08°). The relatively small difference between their mean values, in relation to the magnitude of their standard deviations, explains the significant overlap between the two distributions.

8. *Since the authors used the minor axis to determine particle rotation, rotation around the minor axis is not accessible (I think the authors noted this point as well). Is there any estimate on how much rotation around the minor axis is compared to rotations reported in the manuscript? If not, it's almost impossible to interpret results concerning particle rotation kinematics. I would imagine this quantity becomes more prominent in the round particle case, where authors have reported interesting behaviors.*

   We appreciate the reviewer's comment. The inability to measure rotation along the minor axis of the particles is discussed in the manuscript. Furthermore, due to the lack of texture inside the particle, it cannot be measured using DVC either. However, we believe that rotation around the minor axis has only a secondary effect, primarily influencing energy dissipation at the contact level. In contrast, the particle rotation measured in this study plays a more significant role on fabric, as it directly impacts the orientation of neighboring particles—unlike along-axis rotation. Our findings demonstrate that this particle rotation drives microstructural rearrangement, which in turn influences deformation processes at both the meso and macro scales. The manuscript has been revised to clarify this point as follows:

   "It is important to note that the rotation of the particles along their axis of symmetry is not resolved using the proposed approach. However, this along-axis rotation has only a second-order effect, primarily affecting energy dissipation at the contact level, as it does not influence the orientation of neighboring particles nor the local particle arrangement."

References

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Hall, S. A., Bornert, M., Desrues, J., Pannier, Y., Lenoir, N., Viggiani, G., and Bésuelle, P. (2010). Discrete and continuum analysis of localised deformation in sand using x-ray μct and volumetric digital image correlation. *Géotechnique*, 60(5):315–322.

Pinzón, G., Andò, E., Desrues, J., and Viggiani, G. (2023). Fabric evolution and strain localisation in inherently anisotropic specimens of anisometric particles (lentils) under triaxial compression. *Granular Matter*, 25(1):15.

Tudisco, E., Jailin, C., Mendoza, A., Tengattini, A., Andò, E., Hall, S. A., Viggiani, G., Hild, F., and Roux, S. (2017). An extension of digital volume correlation for multimodality image registration. *Measurement Science and Technology*, 28(9):095401.

Editorial decision

After considering the response from the authors, the managing Editor decided to accept this work for publication without further review.