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Can we study particle breakage in tomography images *Piece-by-Piece*?

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Abstract. The impact of particle breakage on the particle size distribution (PSD) of granular materials is a key element in many engineering applications. High-resolution micro-computed tomography has demonstrated that particle breakage can be observed under various conditions; however, many available methods lack continuous tracking. In this work, a novel and consistent image analysis pipeline, named *Piece-by-Piece*, is introduced to track fragmented particles from the onset of breakage through later stages. The goal is to provide a reliable tool, which is independent of the experiment analysed. Two different study cases are examined: a triaxial test on Ottawa sand particles and a one-dimensional compression test on zeolite granules. In the Ottawa sand test, breakage is successfully tracked throughout the entire experiment with a negligible loss of volume. In contrast, for the Zeolite granules the analysis is terminated before the conclusion of the test, although this does not suggest any deficiency in the tracking algorithm, but rather limitations in image resolution. These results show that continuous particle tracking is possible and serve as a showcase for the enhanced capabilities of *Piece-by-Piece*, which could offer valuable insights into micro-scale breakage mechanics.

1 Introduction

Particle breakage significantly alters the mechanical behaviour of granular materials. Variations in the particle size distribution (PSD) modify micro- and meso-scale interactions, which in turn influence the macroscopic response and strength of the medium. Such phenomena are critical in many engineering applications, from geotechnics to mining and from food processing to manufacturing, where changes in PSD dictate material behaviour under diverse loading and environmental conditions.

A range of constitutive and stochastic models have been developed to capture these effects, aiming to link micro-scale failure events to larger-scale responses [1, 2, 3]. Validation of these micro-inspired models is essential and has been pursued through both single-particle experiments [4, 5] and numerical methods [6, 7].

Understanding how the network of particles responds to breakage is of fundamental importance. Advances in X-ray computed tomography over recent decades, in both laboratory and synchrotron settings, have enabled non-destructive, three-dimensional observations of granular materials under load. *In situ* imaging now allows for the capture of localised strain concentrations at the onset of breakage, as well as the evolution of particle morphology and contact networks as stress increases [8, 6, 9, 10, 11, 12].

Despite these advances, a consistent and robust methodology to characterise the full progression of particle breakage, from the initial micro-scale fracture to the collective macroscopic response, remains lacking. In this paper, a novel approach named *Piece-by-Piece* is presented, which aims to fully integrate image correlation and labelling techniques to track and segment fragments, as well as quantify microscopic changes during breakage. This methodology is evaluated using two complementary experimental tests: a triaxial compression test on Ottawa sand [13] and a one-dimensional compression test on zeolite granules [9].

2 *Piece-by-Piece* pipeline

The *Piece-by-Piece* pipeline is developed to track and analyse the evolution of individual grains in a series of 3D images, with a focus on detecting particle splitting. The method integrates established image processing techniques, including thresholding, phase segmentation [14], the watershed algorithm [15], and discrete digital volume correlation (dDVC) [16], to monitor changes between imaging steps. The pipeline follows five iterative steps (Figure 1):

1. The process starts with a labelled image as the fundamental input.
2. Particles are tracked using dDVC. If breakage prevents convergence, deformation is interpolated from neighbouring converged particles. The particle tracking is then used as a seed for the subsequent re-labelling procedure, which ensures that the IDs are preserved from one step to the next.
3. The surface of the identified particles in both the “reference” and “deformed” configurations is measured *via* the marching cubes algorithm [15].

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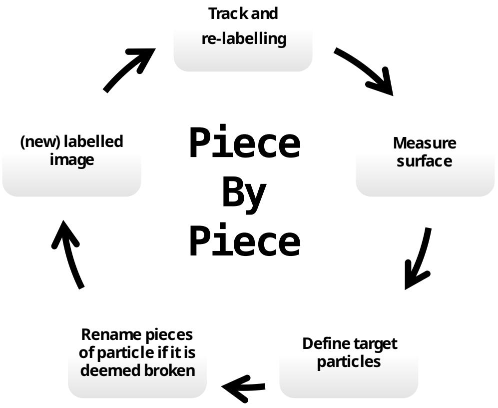

Figure 1: Iterative process of the *Piece-by-Piece* pipeline, highlighting the five key steps for tracking and analysing particle breakage.

4. The measured surface in two sequential steps is compared to detect potentially broken particles (*e.g.*, surface variation > 5%).

5. The greyscale image is masked to isolate the subvolume of individual particles, which is then binarised and re-labelled using a watershed approach. The number of inter-particle flooding points determine if the grain remains intact or has split. Quantitative comparisons with previous steps assess breakage based on volume, moments of inertia, and grey-level statistics to detect false positives.

A label tree records "parent–child" relationships, tracking each grain's evolution and breakage history.

3 Study cases

Two independent experiments are used to evaluate the pipeline.

The first is a triaxial test on monodispersed Ottawa sand (0.5±0.054 mm in diameter) [13]. A 12 mm diameter, 25 mm high sample is progressively loaded axially under a 2 MPa confining pressure. Figure 2 shows the stress–strain curve, where loading drops correspond to relaxation steps during which tomograms are acquired (8 images, voxel size 7.3 μm). As the load increases, reconstructed images highlight particle breakage onset.

The second test is a one-dimensional compression (oedometric) test on zeolite granules (mean diameter 1.36 mm) from Karatza *et al.* [9]. The sample, initially 15 mm in diameter and 12 mm high, undergoes extensive breakage, as seen in the 11 acquired tomograms (voxel size 12.3 μm) shown in Figure 3.

The high-resolution Ottawa sand dataset supports pipeline calibration, particularly in refining detection algorithms and minimising false positives. The more extensive breakage in the zeolite test provides a robust case to assess the pipeline's consistency and versatility.

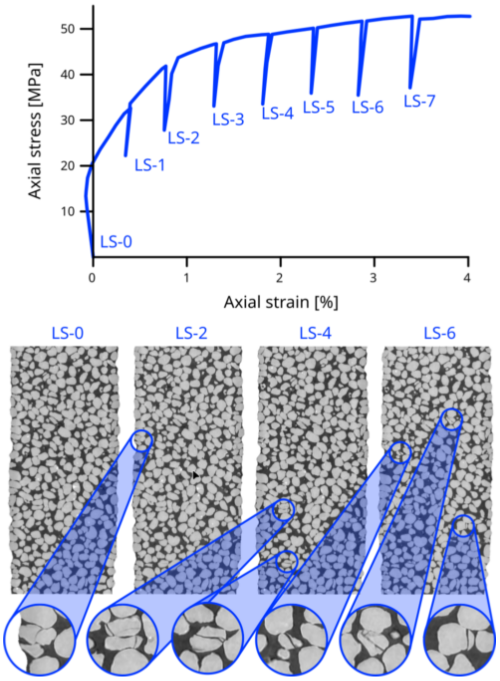

Figure 2: Triaxial compression test on Ottawa sand particles [13]. The test is performed at high confining and axial pressures. Vertical slices of the reconstructed tomograms illustrate the onset of breakage at different loading steps, with more pronounced fracturing observed at higher axial stresses.

4 Results and discussion

The *Piece-by-Piece* pipeline is applied to both datasets to evaluate its ability to track particle breakage across loading steps.

In the Ottawa sand dataset, particles are successfully tracked from the first to the final imaging step, with the number of labelled particles increasing from 3473 to 4130. In the zeolite granules dataset, full tracking is hindered by the "explosive" and extensive breakage. Nonetheless, the analysis extends beyond previous studies [9], up to the LS-04 step, where the number of labels increases from 1074 to 5504. Many of these are below the voxel-based size threshold for reliable particle tracking [16]. It should be noted that particles – whose centre of mass is relatively close to the upper and lower edges of the image – are excluded from both datasets due to imaging artefacts, thus the actual number of fragments is actually higher.

The significant increase in labels in the oedometric test, particularly in comparison to the triaxial test, might suggest that the pipeline is reaching its limits. However, it is important to highlight that the limiting factor is the ratio between the size of the fragments and the resolution of the imaging apparatus, rather than the pipeline itself.

Representative cases are shown in Figure 4, including successfully tracked particles, repeated breakage events, false positive detection, and cases of interpenetrating particles in the Zeolite dataset. Carefully renaming the newly found fragments, it is possible to draw the genealogy of

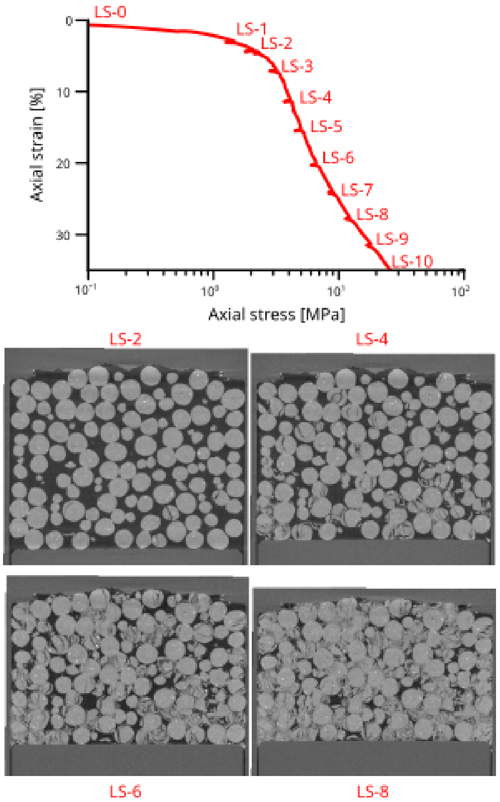

Figure 3: Stress–strain response for the one-dimensional compression test on zeolite granules. Reconstructed tomograms reveal the progressive and extensive breakage of particles as loading increases. Adapted from [6] and [9].

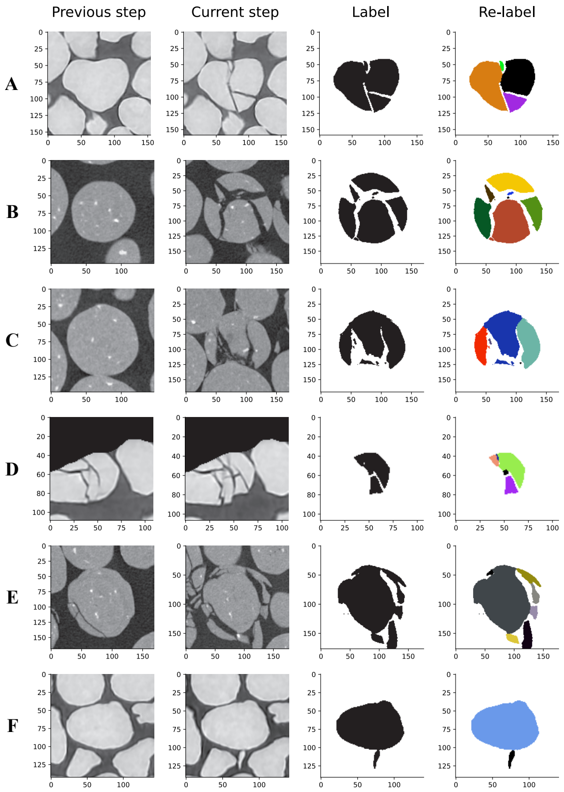

Figure 4: Examples illustrating various instances in which the *Piece-by-Piece* algorithm relabels potentially broken grains. (A) Breakage of an Ottawa sand particle. (B) Breakage of a zeolite granule. (C) Successful labelling despite the interpenetration of zeolite granules. (D and E) An Ottawa sand particle and a zeolite granule breaking a second time. (F) Successful detection of a false positive.

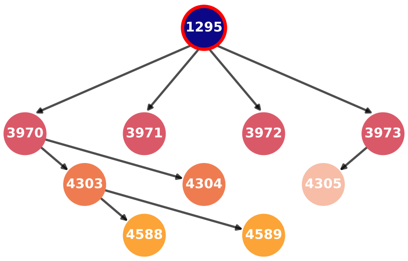

Figure 5: Genealogy of the Ottawa sand particle 1295.

a particle, as shown in Figure 5 for the 1295 Ottawa sand grain. The plot illustrates the fragmentation of the label over successive imaging steps. A false positive is also identified (3973 to 4305), where a neighbouring particle was incorrectly assigned as part of the breakage.

Figure 6 presents the particle size distributions (PSDs) for both experiments, illustrating a reduction in particle size in both cases. Ottawa sand particles experience relatively minor breakage compared to zeolite granules, likely due to differences in experimental configuration.

To assess the reliability of the developed pipeline, volume variations across successive imaging steps were evaluated. Maximum volume variations of approximately 1 % are detected, which is within the sensitivity range of the thresholding and phase segmentation processing. While not all labels, particularly very small ones, can be continuously tracked, the algorithm maintains overall material volume and provides robust and consistent results across both datasets.

5 Conclusions and perspectives

Piece-by-Piece is a novel image analysis pipeline developed to detect, track and quantify particle breakage in 3D X-ray tomography images and its micro-scale implications. The method integrates established techniques: starting from labelled images, discrete digital volume correlation is used to track particle motion, which then serves as a seed for updating particle states. Targeted particles showing substantial changes are further analysed to determine breakage. The algorithm is successfully tested on two independent datasets acquired by different groups, using different imaging setups, materials, and experimental configurations.

The results indicate that, employing a consistent set of parameters throughout the whole analysis, continuous particle tracking is possible with *Piece-by-Piece* in both study cases. In particular, for the instance in which the particles undergo extensive breakage and size reduction, the algorithm appears to be limited by the sensitivity of the imaging apparatus, and not the conceptual framework.

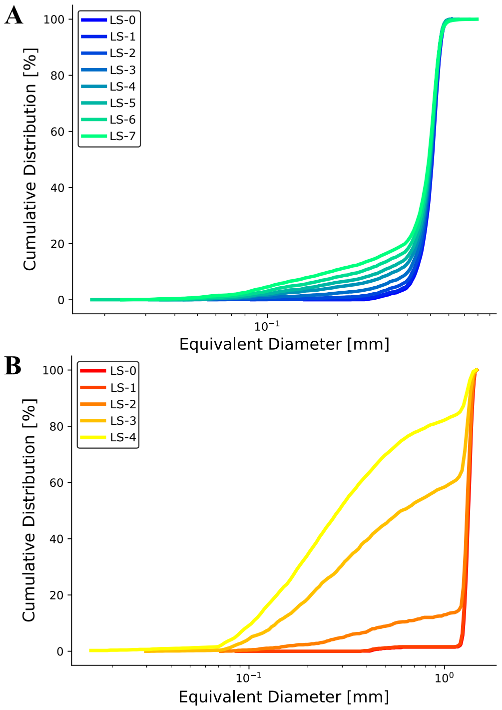

Figure 6: Evolution of the particle size distribution in (A) the Ottawa sand triaxial compression test and (B) the one-dimensional compression of zeolite granules.

Future work will aim to develop a metrological tool to assess the algorithm's accuracy as a function of image quality, and to integrate this functionality into SPAM's `label` toolkit [16]. Further investigation into contact gain or loss events during compression is also planned, as well as bi- or poly-dispersed systems. An extension to two-dimensional systems, particularly for studying splitting phenomena in micro-organisms, represents an interesting extension towards multidisciplinary research.

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