EARLY GRAIN MOTIONS ENCODE INFORMATION ABOUT ULTIMATE FAILURE PATTERN

By Andrew Bartolini
Graduate Student, Department of Civil and Environmental Engineering & Earth Sciences
University of Notre Dame

Materials whose structure is composed of grains (i.e. granular materials), pose a challenge in terms of modeling their behavior and predicting the time and pattern of their failure. A research team at the University of Melbourne under the direction of Antoinette Tordesillas has discovered a link that provides an insight into the ultimate failure pattern of the granular material based upon the motion of the grains early in the loading process of the material. Using a number of different methods to analyze the grain motions, the type and pattern of the failure of a dense granular sample can be predicted. Accurately predicting the failure of granular materials, especially the soils that support structures, has major safety and cost implications.

The first step in the process devised by Tordesillas and her research team is to identify all the 3-cycles that are present in the sample. A 3-cycle is a group of three grains that are all in contact with each other (i.e. a set of three grains where each grain is in contact with the other two grains). The process of identifying the early grain motions is to track these 3-cycles, including the first time that the three grains come in contact with each other (birth) and the time that the three grains lose contact with each other (death). The birth and death patterns of 3-cycles are investigated in both time and space in an attempt to determine trends of the motions of these 3-cycles and determine the ultimate failure pattern. It should be noted that a certain subset of 3-cycles is also investigated, called persistent 3-cycles. These are 3-cycles that have been present from the beginning of the test. The spatial clustering and the statistical trends of when and where these persistent 3-cycles occur in relation to the birth/death of other 3-cycles is also investigated to determine if the persistent 3-cycles provide an improved prediction into the failure of the sample. The 3-cycles hold the ability to predict the future failure pattern because they rotate around the region where the shear band, which is the ultimate failure mechanism, forms. Shear bands are a region of the sample characterized by intense shearing strain, which is correlated with severe deformations. Shearing strain, in a simplistic sense, is the deformations caused when two objects slide past each other. This kind of strain can also happen inside a sample when collections of grains slide past each other. The formation of these shear bands is the main component of the failure of the sample, yet a way to incorporate shear bands into the models of granular materials is an ongoing research question. The Melbourne team strives to achieve a better prediction of the presence of these shear bands by monitoring and analyzing the trends of the 3-cycles and their corresponding grain motions.

Before discussing the results of the study's techniques for predicting the failure and failure patterns (i.e. location of shear bands) of the granular samples, it is important to first see the final failure patterns of the samples. Figure 1 contains images of the failure patterns for two samples. Figure 1a contains the failure pattern for Sample A and Figure 1b contains the failure pattern for Sample B. The failure pattern for Sample A is a single diagonal line and the failure pattern for Sample B is a V shape.

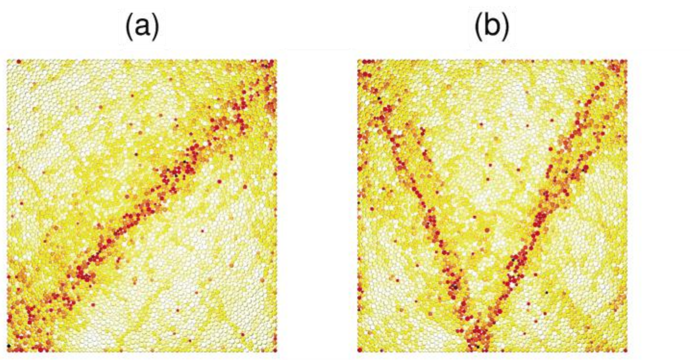

Fig. 1. The pattern of the ultimate persistent shear band as visualized from the accumulated particle rotation over the course of the entire loading history **a** Sample A **b** Sample B.

The importance of the 3-cycles was confirmed early in the study as their motions provided an outline of the future shape of the shear band. As mentioned before, the 3-cycles were predicted to rotate around the shear band, and these predictions were confirmed. Figure 2 shows the motion of the 3-cycles at four different stages of the testing on the samples. The first set of images (a,e) occur before the peak stress, the second set of images (b,f) occur at the peak stress, the third set of images (c,g) occur during the unjamming of the grain particles and the last set of images (d,h) occur during the jamming of the particles. The top row is from Sample A while the bottom row is from Sample B. The diagonal shear band in Sample A is clear as early as the first image, while the V shear band in Sample B becomes evident during the jamming of the grain particles. However, the left leg of the V, which from Figure 1b appears to be the more dominant leg of the shear band, is evident in the first two images of Sample B. From this analysis, 3-cycles appear to hold important information about the future failure patterns of granular materials.

After analyzing the spatial and temporal properties of the 3-cycles, including the total population of 3-cycles at a given moment in time along with their birth and death rates, one particular subset of 3-cycles proved to contain valuable information about the location of the shear bands. This subset comprises the persistent 3-cycles, or the 3-cycles that had remained intact in the sample since the beginning of loading. These persistent 3-cycles represent the stable 3-cycles that are not in the constant flux of birth and death patterns. This is an important distinction, because in a shear band, there is a very high rate of birth and death of the 3-cycles. It is in these locations where the stable persistent 3-cycles do not exist. By spatially tracking the location of persistent 3-cycles and the locations where 3-cycles are being created and destroyed at a high rate, it is possible to identify the locations of these shear bands. Figure 3 contains images of the locations of the persistent 3-cycles from Sample A (a, b) and Sample B (c, d) right after the peak stress (a, c) and at the end of the loading history (b, d). It is clear from these plots that persistent 3-cycles are more densely populated away from the location of the shear bands. These persistent 3-cycles are of vital important in terms of identifying the ultimate failure pattern in the samples.

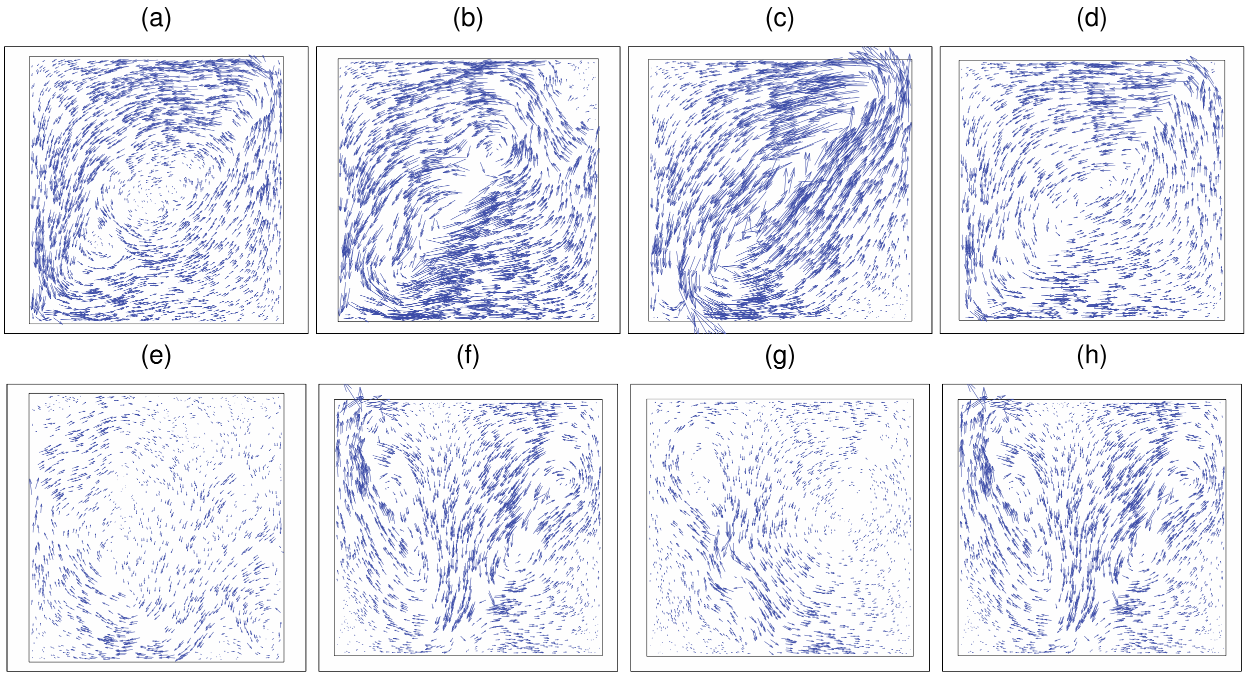

Fig. 2. The 3-cycle displacement fields visualized over key stages beyond the initial strain increment (**a**,**e**) prior to peak stress (**b**,**f**) at peak stress (**c**,**g**) during the unjamming interval (**d**,**h**) during a jamming interval; (**a**-**d**) Sample A, (**e**-**h**) Sample B.

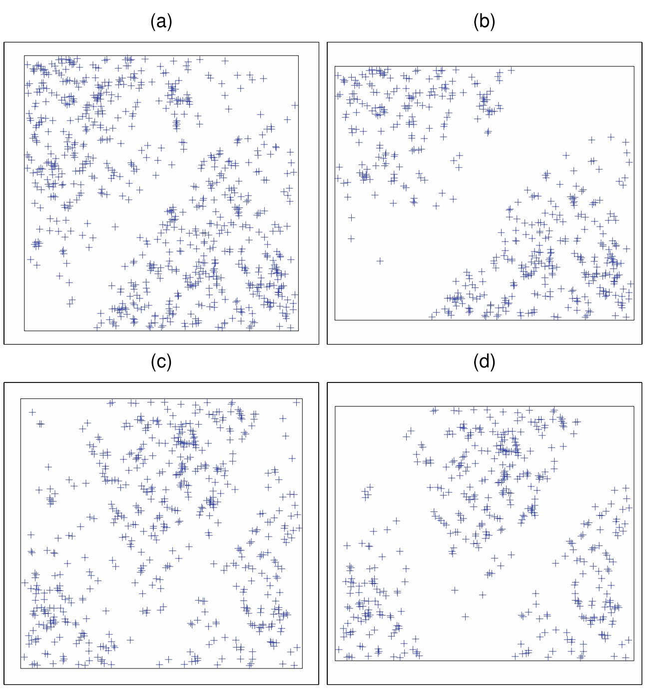

Fig. 3. Spatial visualization of the persistent 3-cycles population (**a**, **c**) just after peak stress, and (**b**, **d**) at the end of loading history: a small circle locates a 3-cycle centroid; (**a**, **b**) Sample A, (**c**, **d**) Sample B.

A final selection from the Melbourne's team research is the art of predicting the mode of failure of the sample (i.e. failure in the presence or absence of shear bands). This is accomplished by identifying when there is clustering of the 3-cycles. The 3-cycles, especially the persistent 3-cycles, tend to cluster in the areas away from the shear bands. Utilizing this fact, the failure of the sample can be predicted. This is seen in Figure 4, which demonstrates this prediction technique for Samples A and B. The research team quantifies the clustering of the 3-cycles and persistent 3-cycles using a clustering factor, termed the "CL Factor." This CL Factor takes the value of one when there is clustering and zero when there is no clustering. The vertical dashed line in each plot represents the peak stress. It is clear from the figures that both methods (all 3-cycles and only persistent 3-cycles) determine there is clustering before the peak stress is achieved. Additionally, persistent 3-cycles seem to provide an even earlier warning signal. It is important to note that in samples where localized failure due to shear bands does not occur, the technique used do not detect clustering, which is also very important in the robustness of this methodology.

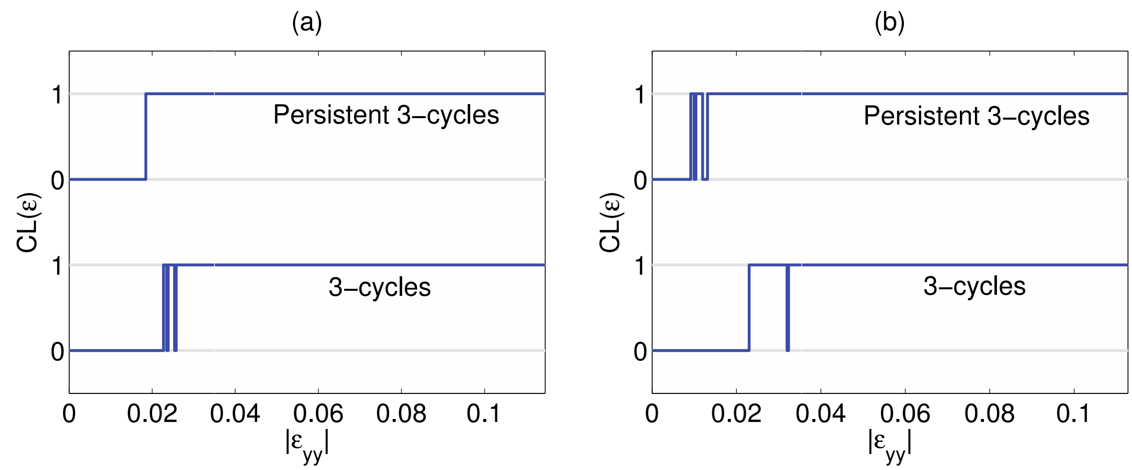

Fig. 4. Evolution with axial strain of clustering indicators CL, for 3-cycles and presistent 3-cycles (solid lines) and strees ratio (dotted line); vertical dashed line marks peak stress; **a** Sample A **b** Sample B

As demonstrated by the research being conducted by Tordesillas and her team, granular motion early in the loading period provides insights into the ultimate failure pattern. The team will continue to apply this approach to other sample configurations in the future while also improving the accuracy of the technique.

The content from this article was adapted from Tordesillas, A, et al. (2014) "Micromechanics of vortices in granular media: connection to shear bands and implications for continuum modelling of failure in geomaterials." *Int. J. Number. Anal. Meth. Geomech.,* John Wiley & Sons, Ltd.