Dilation as a precursor in a continuous granular fault

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Abstract. We analyze the dilation of the system in a cylindrical granular fault consisting of one single layer of disks submitted to both normal pressure and continuous and slow shear, which results in intermittent and sudden energy release events that reproduce the main laws of seismicity. The dilation of the system can be separated into two parts: a smooth increase of dilation, plus sudden changes both contracting and dilating the medium, which are correlated to abrupt jumps -both positive and negative- in the measured resisting torque. We explain the four possible (and existing) general scenarios combining those two variables: dilation jumps and torque jumps, thanks to the assumption of an optimal local angle in the direction of force chains, and each reorganization of the structure as a replacement of the force chain holding most of the applied stress. The average rate of increase of global dilation varies monotonically with the size of the energy release event, making dilation a plausible candidate to predict catastrophic events in such earthquake-like systems.

1 Introduction

Granular systems are often used as analogue experiments mimicking the behavior of a tectonic fault [1–8]. The slow accumulation of energy that is released by sudden events, illustrated with a sandpile in the late 80s [9], and the intrinsic disorder of a granular pile, may indeed generate an intermittent dynamics with a power law distribution of event sizes that qualitatively resembles the one of real earthquakes [3]. The existence of granular gauges as a result of the fracturing processes in the boundaries of adjacent tectonic plates moving relative to each other [10], validates the use of a granular fault as a plausible analogue to a tectonic one. How far the analogies between both systems can hold? Recently an original experimental system developed in our lab in Lyon was able to quantitatively and simultaneously reproduce, with a statistics of more than 1.8 millions of acoustic events, three main laws of seismicity [7]. This strongly suggests that both systems share a common physics and calls for a better understanding of this complex behavior at the granular level. Dilation induced by shear is a classical [11] intuitive phenomenon that we will analyze under our earthquake-like dynamics.

Preliminary results [12] from our experimental system (figure 1) already reported the complex behavior of the dilation, being possible to separate it into two distinct parts (figure 2): one smooth, rather linear dilation (2d), and an intermittent multi-scale discontinuities in both directions (2b): dilation (called jumps) and contraction (called drops), with similar statistical distributions, (2c). In this work we include the analysis of the granular structure, which is able to corroborate the reported behavior, as well as proposing an explanation to the phenomenon, by considering an optimal angle in the direction of the force chains. A more detailed analysis of the correlation between dilation and avalanche size shows a continuous increase of the global dilation rate with the size of upcoming events.

Figure 1. Experimental system. (a) Cylindrical cell containing photoelastic disks. 24 cameras placed in a ring takes images of the granular structure. (b) Close-up showing (1) acoustic sensor, (2) force sensor, and (3) capacitive sensor measuring vertical displacements of the upper plate. (c) Whole granular structure. Notice the force chains with different angles with respect to the vertical direction. (d) Velocity profile showing a clear shear band. The shear speed of the ring driving the system is highlighted.
The position signal $h(t)$ can be split into (d) a smooth dilation $S(t)$ and (b) sudden discontinuities (jumps or drops), denoted as $\Delta h$. (c) Discontinuities distribute following a power-law-like distribution over three orders of magnitude. The time x-axis is shared for all plots except (e).

2 Experimental system

We study a bidisperse mixture of disks confined in one single layer between two concentric fixed acrylic cylinders (figure 1). The disks have been 3D-printed in Duras White 430 material –which is photoelastic– using an Objet30 printer. They have 4 mm thickness and diameters equal to 6.4 mm or 7 mm (in equal proportions). The granular layer is bounded by two rough circular rings where half-grains have been also 3D-printed. A dead load of 20 kg is placed over the top ring compressing the granular pile. The top ring is free to move vertically but not to rotate, while the bottom one is slowly rotated with a period of 18.33 hours, quasi-statically shearing the granular pile with a linear velocity of 48.84 mm/hour. The elastic energy slowly stored due to the shear is liberated by sudden events of all sizes that follows the laws of seismicity [7]. Thanks to a lever and a force sensor, we measure the torque $\Gamma(t)$ applied by the granular pile on the top ring. The vertical displacement $h(t)$ of the top plate, directly measured by the granular layer is monitored thanks to a capacitive sensor. The strict verticality of the force being applied at a given angle by the force chains (see figure 1c). When a force chain breaks, it is intuitive to think that the radial force will decrease and the now less supported top plate will drop ($\Delta h < 0$). However, figure 3 shows counterexamples to this intuitive view: From the three observable jumps, the first two correspond to sudden increases both in torque and $h(t)$, while the last jumps corresponds to a torque drop but with an associated increase of $h(t)$.

Figure 3. Sudden variations in $h$ are simultaneous with sudden variations in resisting torque $\Gamma$.

3 Jumps in dilation and force chains

In our previous report we have shown that the distribution of jumps is similar to a power law for both dilation and contraction events (see figure 2c). Dilation jumps are more numerous, but contraction ones are bigger, dominating the dynamics and globally compensating the smooth increase of dilation [12]. The analysis of the granular structure, particularly the simple inspection of force chains [13–15], brings plausible explanations to the dynamics of jumps in dilation. Jumps are caused by the same re-arrangement of grains as mechanical events are, and occur at the same time, as seen in figure 3. Considering that force is measured radially (as a resisting torque $\Gamma(t)$) and the $\Delta h$ events are related to vertical force (under constant pressure and free volume condition), it seems reasonable to assume that torque and vertical forces are simply orthogonal projections of the same force being applied at a given angle by the force chains (figure 2c). When a force chain breaks, it is intuitive to think that the radial force will decrease and the now less supported top plate will drop ($\Delta h < 0$). However, figure 3 shows counterexamples to this intuitive view: From the three observable jumps, the first two correspond to sudden increases both in torque and $h(t)$, while the last jumps corresponds to a torque drop but with an associated increase of $h(t)$.

To investigate the relationship between these two measurements: $\Delta \Gamma$ and $\Delta h$, we need a procedure to identify which torque discontinuity $\Delta \Gamma$ matches which $\Delta h$. The inter-event time between either kind of measurement is very rarely below 100 ms while the time precision on event detection is in the range of 0.1 ms. We have used a criterion of $\Delta t \leq 1$ ms to consider that both measurements correspond to the same reorganisation event.

Matched events can then be normalized and compared in log-scale. The resulting scatter plot is presented in figure 4, where re-scaled $\Delta h$ are plotted against re-scaled mechanical energy changes (proportional to $\Delta \Gamma^2$ [7]). The scaling factor is, for each series, its detection threshold. In log-scales, it ensures the range of values starts from 0. The released energy associated to a torque drop is considered positive. Therefore a sudden increase of measured torque implies a “negative energy release”.

Intuitively, most points should be in the bottom-right area of the graph (zone D), corresponding to release of mechanical energy and sudden compaction. However, a surprising feature emerges from the data. First, there are more “negative” energy release events than “positive” ones (46% and 54% respectively). Of course, energy is not sud-
Figure 4. Relation between signed and normalized $\Delta h$ values and released mechanical energy, for matched events. A-D: four different behaviors with percentage of events in each classification.

4 Precursory behavior

The results of figure 4 (D-zone) show that high-energy events are strongly correlated with a sudden contraction of the system. This is an indication that a volume increase, i.e., a dilation, is expected preceding those events.

To corroborate this assumption we have analyzed the evolution of the structure of the system around the 33 largest mechanical events. A clear shear band (figure 1d) divides the structure into a very mobile zone, corresponding to a layer of about 10 grain diameters adjacent to the
5 Conclusion

We have analyzed the dilation of a compressed granular fault under slow shear showing the existence of four different behavior associating volume contraction and dilation with positive and negative jumps in the resisting torque. We have explained those behaviors by analyzing the replacement of an active force chain with a new one of a given strength and orientation, and considering the existence of a local optimal angle in the direction of force chains, which place themselves parallelly to the total applied stress. We have also shown that the average rate of increase of global dilation varies monotonically with the size of the energy release event, making dilation a plausible candidate to predict catastrophic events in such earthquake-like systems.

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References

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