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Mimicking earthquakes with granular media

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Résumé :

L'étude des tremblements de terre est d'une importance vitale au vu de leur coût sur la société, tant en termes de vies humaines que de dommages matériels. Malgré cette importance, de nombreuses questions sont sans réponses, comme par exemple la possibilité de prédire les tremblements de terre. Afin de faciliter leur étude au sein même d'un laboratoire, nous présentons ici une expérience originale. Celle-ci imite la dynamique d'une faille tectonique en étudiant un empilement granulaire à deux dimensions qui est à la fois cisailé de façon continue et soumis à une pression de confinement contrôlée. Lorsque les deux « plaques tectoniques » glissent l'une par rapport à l'autre, les contraintes augmentent dans l'empilement jusqu'à ce qu'une réorganisation des grains permette un relâchement de ces contraintes via une avalanche. La distribution des tailles de ces avalanches suit une loi de puissance (analogue à la loi de Gutenberg-Richter). La distribution des temps d'attente entre deux avalanches successives suit aussi la même loi que les tremblements de terre réels, c'est-à-dire une distribution gamma pour l'ensemble des événements, et une distribution de Poisson en ne considérant que les événements de tailles importantes.

Abstract :

Earthquakes study is of vital importance regarding their cost on society, both in terms of human lives and material damages. Although its importance, there are questions still open, as it is the possibility of earthquake prediction. In order to facilitate such a study in a laboratory scale, an original experimental setup is presented in this paper. This setup mimics the dynamics of a tectonic fault by studying a two-dimensional granular layer that is sheared continuously while submitted to a controlled confining pressure. As the "(tectonic) plates" move in relation to each other, shear stresses build up on the packed grains, and eventually the stress of the granular media is liberated through a reorganization of the

pack, an avalanche. The distribution of sizes of these avalanches follows a power law (similar to the Gutenberg-Richter law). The distribution of waiting time between avalanches also follows the same law as real earthquakes, showing a gamma distribution for all the events, and a poissonian process when only large events are considered.

Mots clefs : Avalanches, scale invariance, prediction, earthquakes, granular media, self-organization

1 Introduction

Large earthquakes are one of the most catastrophic events found in nature [1]. Most earthquakes occur at fault zones, where tectonic plates collide or slide against each other. Asperities along the fault surfaces increase the frictional resistance. When the fault is locked, the small relative motion between plates increases the stress. Once the stress is enough to break through the asperities, the stored strain energy is released [2]. It is known that, considering a large statistics, earthquake's energy E distributes according to a power law $P(E) \sim E^{-b}$ with an exponent $b = 5/3 = 1.66$ [3]. The well-known *magnitude* of an earthquake M follows the relation $M = 2/3 \log(E) + K$, where K is a constant value. Notice that in average one catastrophic earthquake with $8 \leq M < 9$ happens every year worldwide.

This scale-invariance (*i.e.*, power-law distribution of events' energy), known as the Gutenberg-Richter law (GR) [4] in the case of earthquakes, is not specific to this phenomenon, but rather common in nature. Phenomena as diverse as snow avalanches [5], granular piles [6–10], solar flares [11, 12], superconducting vortices [13], sub-critical fracture [14, 15], evolution of species [16], and even stock market crashes [17, 18] have been reported to evolve through scale invariant events (commonly denominated avalanches). Considerable efforts have been made to understand the earthquakes dynamics. Mainly from the Geophysical community, but also from the general perspective of scale-invariant avalanches [19–23]. However, many issues remain as open questions, and even the essential fact about the possibility of predicting catastrophic quakes is still a subject of debate [22, 24].

In order to analyze different questions related to earthquakes (and scale-invariant phenomena in general) we present an original experimental setup that mimics the behavior between two tectonic plates. At the frontier between two plates, a planar fracture (the fault) defines the direction of motion. The area around this fracture is called the fault gouge and is composed of crushed rocks from the friction and wear between the two plates. Typically, in order to reduce the complexity, models of earthquake represent the gouge by disks or spheres [25, 26]. We chose this approach in our experiment.

Many different experiments have already tried to simulate the dynamics of earthquakes. These experiments are typically friction experiments or fracture experiments. The friction between two solid blocks have been studied in [27, 28], where they catalog avalanches of different kind depending on the normal force between the blocks. In this case the study generally focuses on the dynamical process of single events. Other friction experiments consisted on the shearing of a granular material [29–31]. On those cases it has been difficult to obtain complex dynamics that resembles the earthquakes dynamics. For instance, in [29] it has been observed an intrinsic response of the system, characterized by a regular stick-slip with all “earthquakes” having approximately the same size. All these friction experiments have a linear geometry. Consequently, the relative motion between the two sliders is limited to a fraction of the length

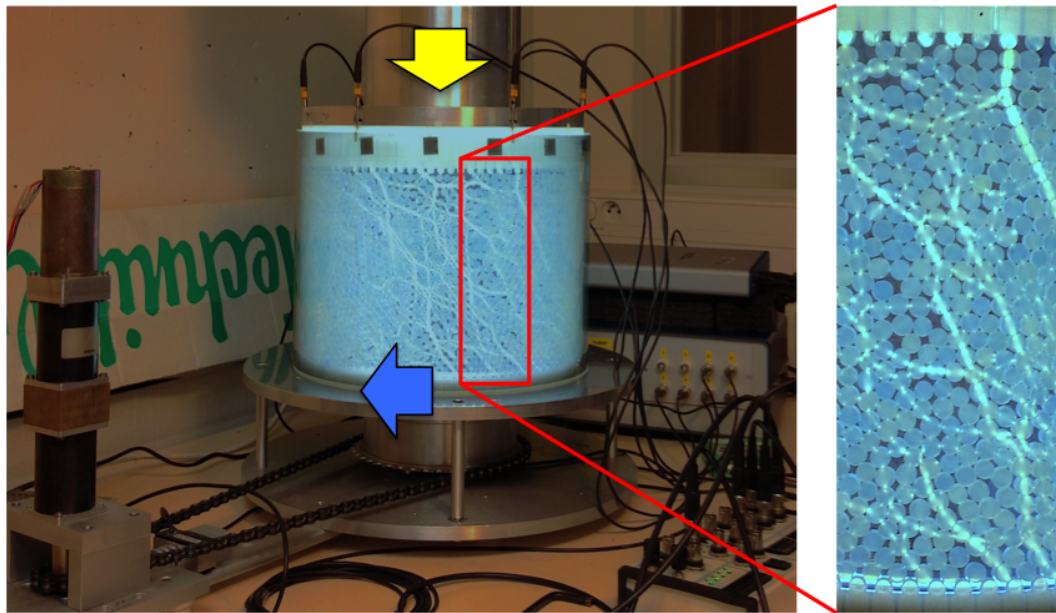


FIGURE 1 – Experimental setup. The yellow and blue arrows represent the confining force and the shear direction respectively.

of the system, which is responsible for the poor statistics. Fracture experiments have also claimed to resemble the earthquakes dynamics : in the case of subcritical fracture [15, 32], different analogies to earthquakes have been found (*e.g.* the Gutenberg-Richter law and the Omori law). However, fracture experiments are, in general, non-stationary and they accelerate towards total failure of the material.

In the present paper we focus on preliminary results of a laboratory “earthquake machine” capable of generating scale invariant events. The setup will consist on a model gouge material, consisting in a granular material, that will be sheared between two surfaces of controlled roughness. As the “plates” move in relation to each other at a controlled torque, shear stresses build up on the packed grains, and eventually they are liberated through a sudden avalanche (reorganization of the pack), with a distribution of sizes following a power law. As it will be detailed in the next section, the experiment has periodic boundary conditions, providing rich statistics.

2 Experimental setup

The experimental setup consists on two fixed, transparent, and concentric cylinders, with a gap between them, so that a monolayer of disks can be introduced into the gap (see Fig. 1). The birefringent nature of the grains allows visualization of the internal force chains in our granular material (close-up in Fig. 1). Two rings containing fixed grains will constrain the pack from upper and bottom boundaries (the yellow arrow in Fig. 1 indicate the force between the plates, fixed by a dead load). As the rings rotate in relation to each other at a controlled and very low speed (blue arrow in Fig. 1), shear stresses build up on the packed beads, and eventually they are liberated through a sudden avalanche. This setup allows for visual and acoustic measurements, apart from the measurement of the force applied on the fixed ring. In the present paper we focus in this last measurement. Being a rotating experiment allows running continuously and the acquisition of rich statistics. Boundaries create very strong (unwanted) effects in friction experiments, so having no boundaries in the direction of motion is also a great advantage of this particular setup.

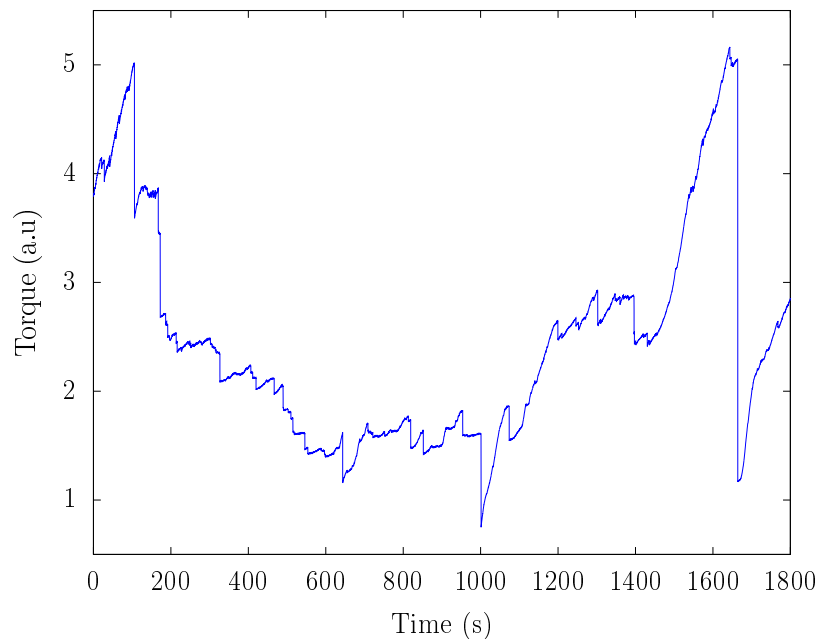


FIGURE 2 – Typical torque signal on a 30 min time window.

We use cylindrical grains of 4 mm thickness and 6.4 mm and 7.0 mm diameter (in equal proportion) to avoid crystallization. These disks are made of Durus White 430 and have been generated in a Objet30 3D printer. The translucent and photoelastic character of the grains allows the visualization of the stress inside the disks when placing the experimental setup between two circular polarizers. The Young modulus of Durus material is $E \simeq 100$ MPa. This contrasts with the classical experiments using photoelastic disks with a Young's modulus $E = 4$ MPa [30, 31, 33–37]. Our grains can hold a much larger stress without a considerable deformation, which favors both the acoustic propagation and image analysis [38].

In order to characterize the dynamics of the sheared material we extract the applied torque over the system thanks to a steel lever and a force sensor SML-900N from Interface (of range 900 N) sampled at 10 Hz.

3 Results

We have measured the resisting global torque necessary to hold the fixed boundary during the shear. The results are encouraging on our ability to reproduce earthquakes-like dynamics. Indeed, from this measure, we can observe a continuous loading interrupted by intermittent drops of various sizes (see Fig. 2), characteristic of a very irregular stick-slip-like motion. These drops are the signature of sudden global reorganizations of the pile, *i.e.*, avalanches. The name avalanche is clearly adapted in this case, since from a single grain exceeding its threshold and moving, a great number of other grains will reorganize and release their accumulated stresses. This stress release will manifest itself by a very brief decrease of the applied torque on the top boundary. By plotting the derivative of the resistive torque, the avalanches appear as peaks (see Fig. 3), which heights define the sizes of the avalanches.

From a very long series of events, typically during a few days, and representing a few ten thousands of events, we can plot the probability distribution of the avalanches sizes (see Fig. 4). What we observe is

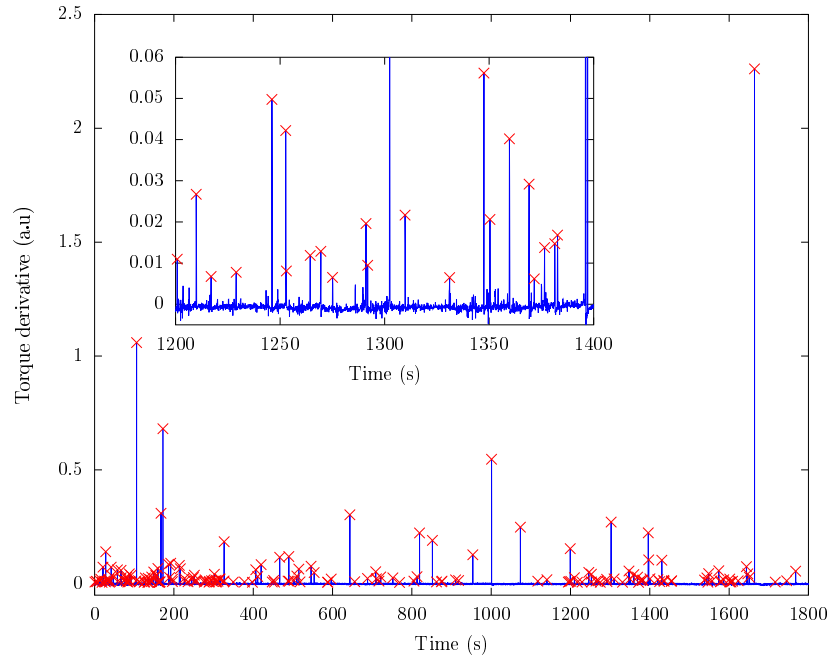


FIGURE 3 – Derivative of the torque measurements of Fig. 2. Red crosses represent the detected events. Since the amplitudes scale on 3 decades, the small events seem to appear in the noise but they are clearly visible when zooming (see the inset).

that the distribution follows a power law at small sizes and reaches a cutoff at very large sizes (typically greater than 1 on Fig. 4). This regime is characterized by very low statistics (it represents less than 1% of the whole set of events), so it is difficult to fit a precise behavior. For the power-law regime, we can extract an exponent 1.64 ± 0.04 . This power-law regime is comparable with the GR law, however notice that we obtain it as the distribution of torque drops, where the GR law deals with the energy of earthquakes.

Apart from the amplitude informations about avalanches, we also have access to their temporal occurrences, and in particular the waiting times between two successive avalanches. If we plot the distribution of waiting times for all avalanches (see Fig. 5), we get a generalized gamma function behavior scaling like $\tau^{-\gamma} \exp[-(\tau/\tau_0)^\delta]$ with $\gamma = 0.30 \pm 0.05$, $\tau_0 = 9.5 \pm 0.5$ s and $\delta = 0.80 \pm 0.04$, which is consistent with the behavior extracted from real earthquakes data in [39]. By looking at the waiting times between only the large events (amplitude greater than 0.5), then we get an exponential behavior $\exp(-\tau/\tau_l)$ with $\tau_l = 195 \pm 5$, which means that the large events are independent.

4 Conclusions

In conclusion we have presented an experimental setup that reproduces at the laboratory scale the avalanche-like dynamics of earthquakes. Our model “earthquake machine” consists of two concentric cylinders separated by a gap that allows only a bidimensional layer of disks between the two cylinders. This mimics the dynamics between two tectonic plates separated by a model gouge material. In order to characterize the mechanical response of the sheared material we have measured the torque applied by the system on a fixed boundary. The results present an intermittent behavior characterized by irregular stick-slip-like dynamics. We have characterized the statistical properties of the resulting avalanches, and found a good consistency with real earthquakes behavior. In particular, we have shown that the size

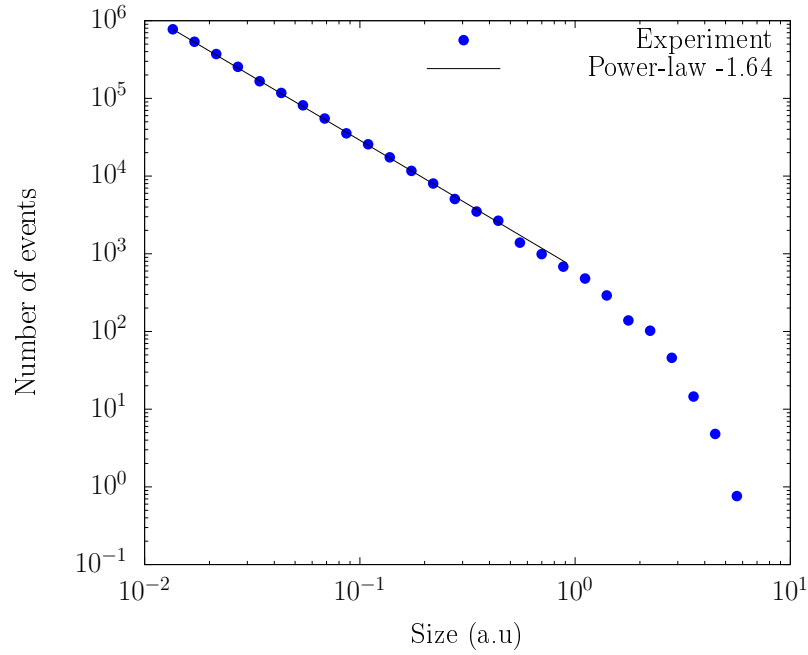


FIGURE 4 – Avalanches size distribution from a 6 days experiment, representing ~ 50000 events.

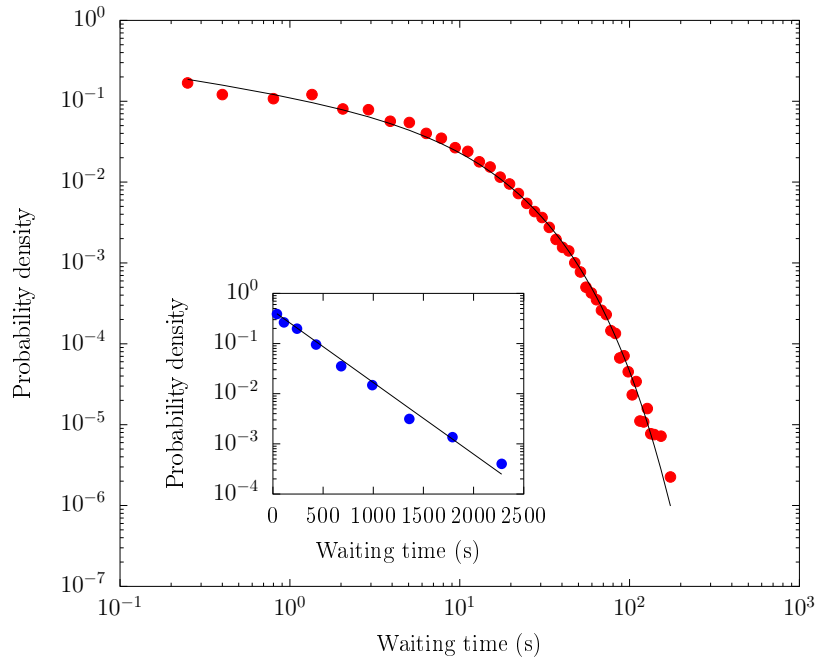


FIGURE 5 – Waiting times probability distribution for the whole set of avalanches detected in Fig. 3. The solid line is a fit to the data of a generalized gamma distribution. The represented gamma distribution has the form $\tau^{-0.3} \exp \left[-(\tau/9.5)^{0.8} \right]$. The inset is the probability distribution of waiting times for only large events (sizes greater than 0.5, representing $\sim 3\%$ of the events). The straight line is a fit to the data representing an exponential distribution characterized by $\exp(-\tau/195)$.

distribution of the avalanches follows a power-law for low and medium sizes, which corresponds to the Gutenberg-Richter law for earthquakes. At larger sizes we observed a faster decay on the number of events, that cuts off our distribution of avalanche sizes. We have also observed that the waiting times distribution between all events is compatible with the one found using earthquakes catalogs [39].

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