



HAL
open science

Absorbent Porous Paper Reveals How Earthquakes Could be Mitigated

G. Tzortzopoulos, P. Braun, Ioannis Stefanou

► **To cite this version:**

G. Tzortzopoulos, P. Braun, Ioannis Stefanou. Absorbent Porous Paper Reveals How Earthquakes Could be Mitigated. *Geophysical Research Letters*, 2021, 48 (3), 10.1029/2020GL090792. hal-03168395

HAL Id: hal-03168395

<https://hal.science/hal-03168395>

Submitted on 13 Mar 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Not subject to U.S. copyright. Accepted for publication in *Geophysical Research Letters*.
2 Published in 2020 American Geophysical Union. Further reproduction or electronic distribution
3 is not permitted.

4 **Absorbent porous paper reveals**
5 **how earthquakes could be mitigated**

6 **G. Tzortzopoulos¹, P. Braun¹, I. Stefanou¹**

7 ¹Institut de Recherche en Génie Civil et Mécanique, Ecole Centrale de Nantes
8 1 Rue de la Noë, Nantes 44321, France

9 **Key Points:**

- 10 • From an energetic point of view, absorbent porous paper can be an ideal, low-cost
11 surrogate rock material for studying induced seismicity.
12 • Segmentation of faults and sequential fluid injection in each segment can mitigate
13 potential earthquakes by at least one order of magnitude.
14 • We show that fault segmentation, segment-activation rate and stress state predominantly
15 control the result of applied injection strategies.

Corresponding author: Ioannis Stefanou, ioannis.stefanou@ec-nantes.fr

Abstract

Earthquakes nucleate when large amounts of elastic energy, stored in the earth's crust, are suddenly released due to abrupt sliding over a fault. Fluid injections can reactivate existing seismogenic faults and induce/trigger earthquakes by increasing fluid pressure. Here we develop an analogous experimental system of simultaneously loaded and wetted absorbent porous paper to quantify theoretically the process of wetting-induced earthquakes. This strategy allows us to gradually release the stored energy by provoking low intensity tremors. We identify the key parameters that control the outcome of the applied injection strategy, which include the initial stress state, fault segmentation, and segment-activation rate. Subsequent injections, initiated at high stress levels, can drive the system faster towards its instability point, nucleating a large earthquake. Starting at low stress levels, however, they can reduce the magnitude of the natural event by at least one unit.

Plain Language Summary

Understanding natural and anthropogenic seismicity is a major scientific challenge. Here we present a novel analogue fault model using absorbent porous paper, which gives new insights on earthquake mitigation. When scaled to in-situ conditions, the porous paper model represents a natural seismic rupture of magnitude $M_w = 5.9$. By progressively wetting it, we simulate fluid injections in the earth's crust and draw analogies to large-scale industrial projects. In our experiments, each injection is accompanied by tremors, which progressively release energy and modify the energy budget of the system. Without precise knowledge of the fault properties, we risk driving the system faster towards an unexpected large seismic event. However, provided that the model's key parameters - fault segmentation, segment-activation rate, and stress state - are well known or controlled, the natural rupture can be mitigated by at least one unit. We expect that these results will facilitate risk reduction in current fluid injection projects and inspire earthquake mitigation strategies for real tectonic faults.

1 Introduction

It is well recognized today that humans can cause earthquakes (Raleigh et al., 1976; McGarr et al., 2002; Guglielmi et al., 2015; Foulger et al., 2018). Examples of anthropogenic seismicity involve earthquakes provoked by large artificial water reservoirs such as dams (Gupta, 2002), mining (Li et al., 2007), underground nuclear explosions (Hamilton et al., 1972) or by fluid injections in the earth's crust (Ellsworth, 2013; Rubinstein & Mahani, 2015; Garagash & Germanovich, 2012; Schultz et al., 2020). The latter type of anthropogenic seismicity is of particular interest, due to the numerous ongoing industrial applications (Rubinstein & Mahani, 2015; Hosseini et al., 2018). These anthropogenic seismic events could shift the Gutenberg and Richter (1954) power law, which describes the relationship between the total number of earthquakes and their magnitudes, towards smaller events.

This idea is similar to the one traditionally used for reducing the risk of large snow avalanches. Snow avalanches follow the same frequency-magnitude distributions as natural earthquakes do (Birkeland & Landry, 2002). Nowadays, it is common practice to avoid large avalanches by provoking smaller ones. Similarly, large earthquakes could be probably mitigated by inducing low intensity tremors. This is what is called here earthquake mitigation. This notion was first mentioned by Raleigh et al. (1976), but has not been explored further since.

Surrogate materials can effectively substitute in-situ rock and gouge materials (Rosenau et al., 2017). Some examples of such materials are sandpaper (King, 1975), cardboard (Heslot et al., 1994), pasta (Knuth & Marone, 2007), steel (Popov et al., 2012), hydrogel (Latour et al., 2013) and puffed rice (Einav & Guillard, 2018). Here we use absorbent porous paper as an analogue fault material to explore earthquake mitigation. We show

65 that it can be an ideal low-cost surrogate material for reproducing earthquake-like instabilities
 66 in the laboratory. Wetting the absorbent paper allows us not only to weaken the material
 67 but also to induce small instabilities. By deriving adequate scaling laws (see supporting
 68 information §6), we can simulate fluid injections and study the transition from seismic
 69 (unstable, sudden) to aseismic (stable, creep-like) slip of an ideal fault (Stefanou, 2019;
 70 Cappa et al., 2019).

71 2 Paper-quakes vs. earth-quakes

72 Consider an isolated planar dip-slip fault, as depicted in Figure 1a, with a length
 73 of $L_{ac}^{real} = 6.5$ km dipped at an angle of 60° (see also supporting information §5). Based
 74 on its properties and assuming a square rupture area ($A^{real} \approx (L_{ac}^{real})^2$), this fault leads
 75 to an earthquake of $M_w \approx 6$ (see supporting information §6). The energy budget is contained
 76 in a single sheet of absorbent paper which, consequently, can represent this fault (see also
 77 supporting information §1-2) if strained as shown in Figure 1b. Long range interactions
 78 with other faults are not considered herein.

79 The energetic equivalence of the paper analogue with a real fault can be observed
 80 in Figures 1c-e. The progressive accumulation of elastic energy in the rocks surrounding
 81 the fault zone is taken into account by a spring attached at the one end of the sheet (Figures
 82 1d-e). The apparent stiffness of the spring is chosen to represent the real system. A constant
 83 slow velocity is applied at the extremity of this spring, simulating the slow far-field tectonic
 84 loading. Finally, paper has a non-negligible softening branch that simulates the critical
 85 slip distance d_c of faults (Scholz, 2002) (Figure 1f).

86 We can also simulate fluid injections by simply wetting the paper sheet. In a fault
 87 system, the apparent friction drops when fluids under pressure are injected into the fault
 88 zone due to the decrease of the effective normal stress. Similarly, porous paper shows
 89 a noticeable stress drop when it is wetted due to the reduction of its strength (Figures
 90 1f and 2c). The ratio of the shear stress drop of real faults to the strength weakening
 91 of porous paper is defined here by the scaling factor a , which is a free parameter in our
 92 model (see also supporting information §6). Finally, opposite to wetting, healing could
 93 be considered by drying the paper stripes, which could potentially lead to repeatedly growing
 94 slip events. However, this is out of the scope of the present work, which focuses on earthquake
 95 mitigation by fault reactivation.

96 Notice that the fluid diffusion process which takes places during injections in wellbores
 97 can be considered in our analogue model in two ways, by water absorption of porous paper
 98 and by progressive wetting of many isolated stripes (see Figures 1b and e and Section
 99 4). Assuring that tectonic loading is much slower (see Section 5 for more details) than
 100 diffusion, only the latter way is examined here.

101 The configuration shown in Figures 1b and e leads to a sudden release of the elastic
 102 energy upon rupture, in the same way as the energy stored in the rocks surrounding the
 103 fault zone is released during an earthquake. Note that typical failure modes II and/or
 104 III that take place during seismic slip in faults are represented here by a mode I failure
 105 of the porous paper. These systems are equivalent in terms of energy budget (Nussbaum
 106 & Ruina, 1987), provided that appropriate scaling laws are applied. By using these scaling
 107 laws (see supporting information §6) and measuring the elastic energy E_R^{paper} that accompanies
 108 paper failure in the surrogate system, one can estimate the earthquake magnitude M_w
 109 of the real system as follows:

$$110 \quad M_w = \frac{2}{3} \log_{10} (E_R^{paper}) + 6.36 \quad (E_R^{paper} \text{ in Nm}) \quad (1)$$

111 In Figure 2a, we present the force-displacement evolution of a paper sheet that is
 112 put under tension as described above. In the beginning, the porous paper shows a linear

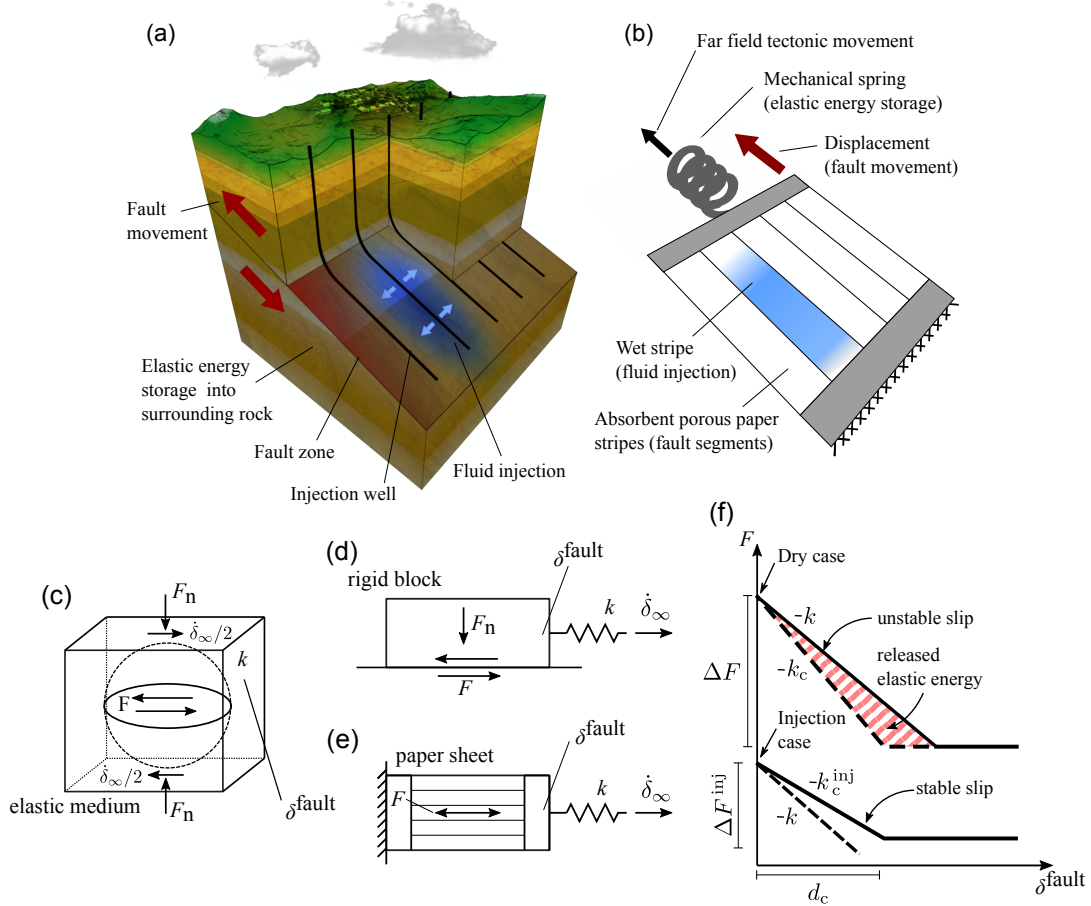


Figure 1. (a) Simplified dip-slip fault where the fault zone area is divided in five segments parallel to the slip direction. Five wells allow to inject fluid into each segment independently. (b) Surrogate laboratory experiment consisting of five parallel stripes of absorbent paper, held together at their ends by clamps. Far-field movement is applied through a mechanical spring. The paper stripes can be wetted individually. (c) Pre-existing fault within an elastic medium of stiffness k , loaded by a very low velocity, $\dot{\delta}_\infty$. Normal forces F_n act on the fault, while frictional forces F are generated along the interface (Reid, 1910). (d) Spring-slider model (Scholz, 2002), composed of a rigid block, which is pulled through a spring over a rough surface. (e) Paper-spring model, where a stripe of paper is pulled through an elastic spring. (f) Schematic force-displacement diagram in which the post-peak properties are modified due to fluid injection on the fault (wetting in the porous paper case), allowing transition from unstable to stable slip.

113 behavior up to its peak strength. Then, a fracture appears in the paper sheet and the
 114 spring is unloaded abruptly. The energy that is released during the unloading is equal
 115 to $E_R^{\text{paper}} = E_R^0 = 0.201 \text{ Nm}$ (hatched area), corresponding to an equivalent earthquake
 116 of $M_w = 5.9$ according to Eq. (1). This dynamic instability can also be observed by
 117 the velocity pulse shown in Figure 2b, illustrating the analogy between paper-quakes and
 118 earth-quakes (Kanamori & Brodsky, 2004) (see also supporting information Movie S1).

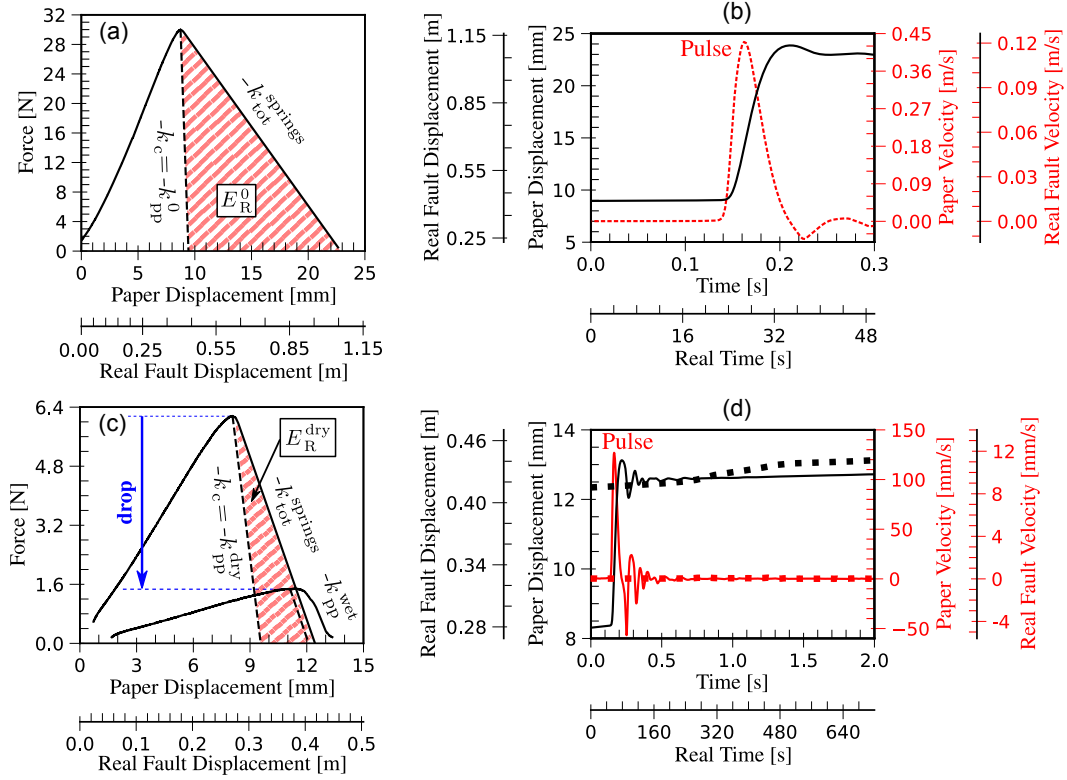


Figure 2. (a) Force-paper displacement diagram of a paper sheet experiment, showing paper behavior without a spring (dashed line) and with a spring attached to one end (solid line). (b) Pulse-like velocity (dotted line) of the dynamic paper sheet experiment, with corresponding slip (solid line). (c) Force-paper displacement diagram of representative dry and wet experiments, for a single paper stripe. Post-peak slope reduction ($k_{pp}^{dry} > k_{pp}^{wet}$) and force drop are observed. In this example, a dynamic instability happens in the dry case ($k_{tot}^{springs} < k_{pp}^{dry}$) releasing energy E_R^{dry} . In the wet case no instability occurs ($k_{tot}^{springs} > k_{pp}^{wet}$). (d) Paper displacement (black) and velocity (red) evolution with time for dry (solid lines) and wet (dotted lines). The stabilizing effect of wetting is apparent. The additional axes scale the respective quantities to the real fault case (cf. supporting information §6).

119 3 From seismic to aseismic rupture

120 A seismic rupture, i.e. an earthquake, is a dynamic instability that happens when
 121 the (elastic) unloading of the rocks surrounding the fault zone cannot be counterbalanced
 122 by fault friction. A necessary but not sufficient condition for the occurrence of this instability
 123 is the reactivation of the fault. We say that a fault is reactivated when the shear stress
 124 on the fault area is high enough for frictional slip to take place. However, this slip can
 125 be slow (aseismic) or sudden and abrupt (seismic), depending on the amount of slip weakening
 126 (Figure 1f). It can be shown that the condition for sudden, unstable slip is (Dieterich,
 127 1979; Scholz, 2002; Kanamori & Brodsky, 2004; Stefanou, 2019):

$$k < k_c = \frac{\Delta F}{d_c} \quad (2)$$

128 where k is the apparent stiffness of the rocks surrounding the fault zone for the real system,
 129 and k_c is the critical stiffness. In a real scenario, the drop of shear force is $\Delta F = A^{\text{real}} \Delta \tau^{\text{real}}$,

130 where $\Delta\tau^{\text{real}}$ is the apparent shear stress drop of the fault zone. The stiffness k is proportional
 131 to the effective elastic shear modulus of the surrounding rocks G^{real} , and inversely proportional
 132 to the fault length $L_{\text{ac}}^{\text{real}}$, i.e. $k \propto G^{\text{real}}/L_{\text{ac}}^{\text{real}}$. Moreover, according to Coulomb friction
 133 $\tau = \mu\sigma'_{\text{n}}$, where $\sigma'_{\text{n}} = \sigma_{\text{n}} - p_{\text{w}}$ is the effective normal stress, σ_{n} is the total normal
 134 stress, which is a fraction of the overburden load, depending on the tectonic setting, and
 135 p_{w} is the fluid pressure.

136 Therefore, fluid injections have a double effect. On the one hand, they can reactivate
 137 a fault by increasing p_{w} , reduce friction and promote frictional slip (Cappa et al., 2019).
 138 On the other hand, they can reduce k_c as they make the post-peak slope less steep (Scuderi
 139 et al., 2017; Lockner et al., 1991) (Figure 1f). Consequently, in an earthquake mitigation
 140 attempt, one could adjust fluid pressure in such a way to avoid sudden, seismic slip and
 141 assure stable, creep-like rupture (Stefanou, 2019).

142 4 Earthquake mitigation by fault segmentation and fluid injections

143 Controlling the fluid pressure simultaneously, across an entire fault of several kilometers,
 144 seems impossible with current technologies. Yet, we could imagine to divide the potential
 145 rupture area into several zones and inject fluids through a network of well-bores (Figure
 146 1a). In this way, the energy stored in the system could be in theory released gradually,
 147 mitigating the maximum earthquake magnitude.

148 The rupture area of our fault scenario is divided into five segments and so is the
 149 paper sheet, as shown in Figures 1a-b. In order to have a better understanding of the
 150 behavior of the segmented paper sheet (Figure 1b) under wetting, we tested first a single
 151 segment (Figure S4a). In Figure 2c, we show the transition from seismic rupture to an
 152 aseismic one by wetting. While the dry sample fails suddenly, liberating energy $E_{\text{R}}^{\text{dry}} =$
 153 9.2 Nmm (hatched area), the wet sample fails progressively with $E_{\text{R}}^{\text{wet}} \approx 0$, i.e. aseismically
 154 (see also supporting information Movie S2).

155 Figure 2d corroborates the aseismic failure of the single stripe when wet. In particular,
 156 the time-profiles of displacement and velocity are presented and compared for both dry
 157 and wet samples. While the dry sample slips abruptly, the wet sample reaches the same
 158 displacement in an almost constant, slow velocity, which is two orders of magnitude smaller
 159 than the peak velocity of the dry case (see also supporting information Movie S2). If we
 160 apply our scaling laws on the experimental data (see supporting information §6), the dry
 161 single-stripe test gives an earthquake of magnitude $M_{\text{w}} = 4.5$, which is nucleated in
 162 a normal fault with a length of $L_{\text{ac}}^{\text{real}} = 1.3 \text{ km}$.

163 Focusing on our surrogate experiment, five stripes (see supporting information Figure
 164 S4b) are put in tension and are wetted subsequently to simulate multiple discrete fluid
 165 injections. A certain amount of fluid is injected each time assuring fast saturation all over
 166 the respective fault segment. Until the completion of the injection strategy, no more fluid
 167 is injected on an already saturated segment. The injection program starts before reaching
 168 instability, at a stress level $R = 20\%$ (Figure 3a), where R is the ratio of the tensile force
 169 at the first injection over the maximum tensile resistance. Wetting one stripe is performed
 170 approximately every 1 mm of total displacement (segment-activation rate = 3 stripes/min).
 171 This displacement corresponds to $\sim 5 \text{ cm}$ of average slip over the real fault zone (see also
 172 supporting information §4 and Movies S1 and S3).

173 Each fluid injection is accompanied by an instantaneous stress drop and stress redistribution
 174 over the intact, dry porous paper stripes (Harris, 1998; Cappa et al., 2019) (Figure 3a).
 175 In this setup, the redistribution is quasi-uniform and may not capture phenomena related
 176 to real fault geometries. Due to these stress drops, energy is released abruptly, corresponding
 177 to the triggering of small dynamic events (hatched areas). Ideally, we would like to minimize
 178 their magnitudes or assure aseismic slip after each injection. The maximum magnitude

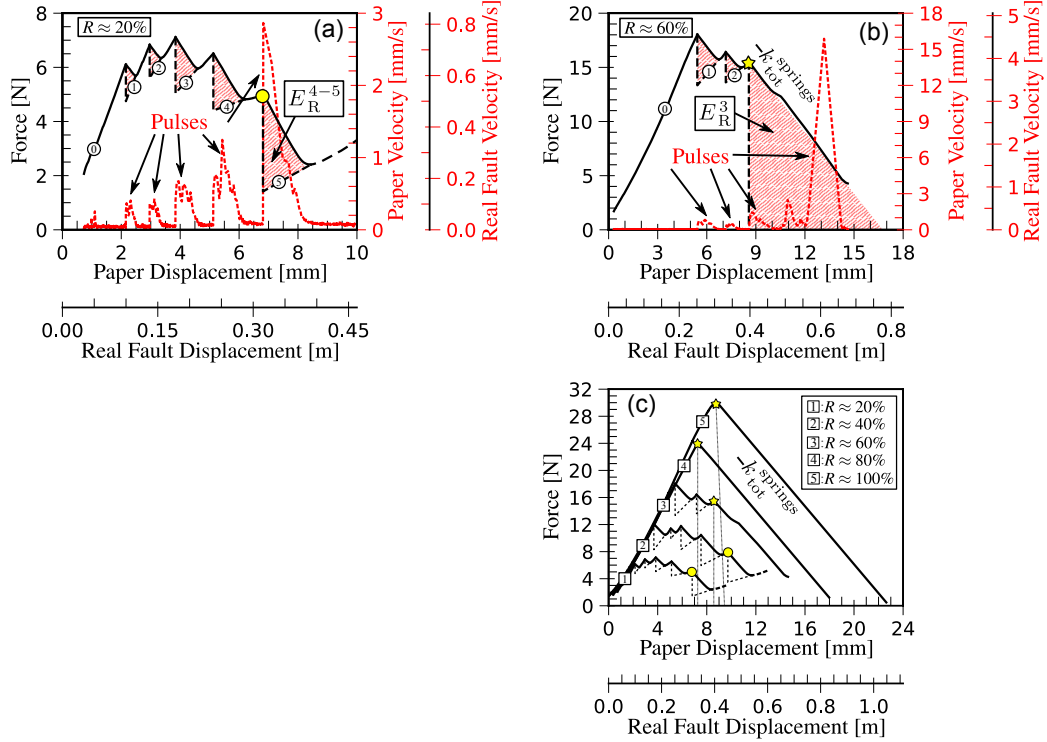


Figure 3. Wetting scenarios starting at $R = 20\%$, (a), and $R = 60\%$, (b). Force (equivalent friction, solid lines) and velocity (equivalent slip-rate, dotted lines) evolve with displacement (equivalent slip). Circled numbers depict the number of wetted paper stripes (reactivated fault segments). In (a), the maximum earthquake event takes place at the fifth injection (filled circle) and releases E_R^{4-5} . In (b), the sample fails dynamically at the third injection (star) and all remaining elastic energy is released abruptly (rupture of the entire fault area outside the injection area). (c) Force-paper displacement for scenarios started at different stress levels R . The star indicates that global failure occurs before wetting all the stripes (i.e. rupture outside the injection region).

179 among these smaller events characterizes the effectiveness of the earthquake mitigation
 180 strategy.

181 Figure 3a shows the energy release and the developed velocities during this injection
 182 program in our experiment. In the same plot we present also the corresponding magnitudes
 183 of displacement and velocity that would develop in the real fault system. A sequence of
 184 dynamic events are triggered with magnitudes: $M_w^{0-1} = 3.9$, $M_w^{1-2} = 3.9$, $M_w^{2-3} =$
 185 4.3 , $M_w^{3-4} = 4.4$ and $M_w^{4-5} = 4.7$. It is worth emphasizing that the released energy
 186 increases with subsequent slip and it is maximum after the last injection ($E_R^{4-5} = 2.94$ Nmm),
 187 which is 68 times smaller than the energy of the large natural event. Therefore, we were
 188 able to mitigate the initial natural earthquake event of magnitude $M_w = 5.9$ to five
 189 smaller earthquake events, whose maximum magnitude (filled circle in Figure 3a) is $M_w =$
 190 4.7 . In terms of velocities (dotted line in Figure 3a), after each injection, we observe a
 191 distinct pulse corresponding to the released dynamic energy.

192 The system behaved differently when the injections started at a stress level ratio
 193 $R = 60\%$ (Figure 3b, see also supporting information Movie S4). In this case, three dynamic
 194 events are triggered with magnitudes: $M_w^{0-1} = 4.7$, $M_w^{1-2} = 4.5$ and $M_w^3 = 5.5$. A

195 large event followed the third injection (filled star in Figure 3b), leading to seismic rupture.
 196 Energetically, this event ($M_w^3 = 5.5$) is equivalent to the natural earthquake event ($M_w =$
 197 5.9 , see also Figures 2a-b).

198 In Figure 3c, we show the energy release for injections started at different stress
 199 level ratios with the same segment-activation rate as before. In the case of $R \approx 100\%$,
 200 no injection can be carried out, as any tiny perturbation leads directly to an earthquake
 201 nucleation (filled star) of magnitude $M_w^0 = 5.9$ (Figures 2a-b). At $R = 40\%$, all five
 202 injections are accomplished as in $R = 20\%$. These injections result in a series of five
 203 induced earthquakes where their maximum magnitude (filled circle) is $M_w^{4-5} = 4.8$. When
 204 $R = 80\%$, though, a dynamic rupture occurs (filled star) after the first injection leading
 205 to an earthquake event of $M_w^1 = 5.8$, similar to the case of $R = 60\%$ (Figure 3b).

206 The experimental observations show clearly that as the stress level at the initiation
 207 of the injection process becomes smaller, so does the magnitude of the subsequent events.
 208 In other words, a sequence of earthquakes could be triggered, showing a maximum magnitude
 209 which is at least one order of magnitude smaller than the natural earthquake.

210 Notice that our study is in agreement with the findings of the modeling work of
 211 van der Elst et al. (2016). As we can observe in Figure 3c, the natural earthquake event
 212 (curve 5) is the maximum event that can be nucleated in a fault in terms of energy, no
 213 matter how much fluid volume has been injected into the fault and no matter when the
 214 injection commences.

215 5 Discussion

216 The proposed analogy between uniaxial tension experiments of absorbent porous
 217 paper and a real fault system is based on energy considerations. Our model is a pertinent
 218 example for building understanding regarding possible mitigation of the earthquake phenomenon
 219 (for a synthesis of the main assumptions and limitations we refer to the supporting information
 220 §7). Intuitively, our approach could help to limit anthropogenic seismicity (Shapiro et
 221 al., 2013) during fluid injections in the earth's crust, in parallel with the Traffic Light
 222 System (TLS) method (Bommer et al., 2006; Edwards et al., 2015) used in deep geothermal
 223 projects.

224 It is worth emphasizing that, according to our experiments, preceding small seismic
 225 events do not guarantee the avoidance of large ones. Even though the released energy
 226 in induced events is always smaller than the natural event, subsequent injections can drive
 227 the system faster towards its instability point, provoking a large event (Figures 3b-c).
 228 These events ($R = 60\%$ and 80% in our experiments) would correspond to anthropogenic
 229 seismicity when significant amounts of fluid are injected in the earth's crust, close to critically
 230 stressed tectonic faults. On the other hand, we showed scenarios of progressive wetting,
 231 where the maximum seismic moment could be reduced by one order of magnitude (Figures
 232 3a and c). An important aspect, necessary for the possible mitigation in this scenario,
 233 is the relatively low initial stress level ($R = 20\%$ and 40% in our experiments). Therefore,
 234 the earthquake mitigation strategy can succeed only if the injection process starts at relatively
 235 low stress levels.

236 Besides the in-situ stress level, the paper experiments uncovered two additional factors
 237 which govern the magnitude of induced events. These factors are the segment-activation
 238 rate, which expresses the number of segments that are wetted per unit of time, and the
 239 number of segments that our samples are divided into. In order to explore the response
 240 of the fault system under the variation of these two additional factors, we use a multi
 241 spring-slider model (see supporting information §3-4).

242 The segment-activation rate can be seen as the rate under which we force the system
 243 to release its internal (potential/elastic) energy. According to our experiments and this

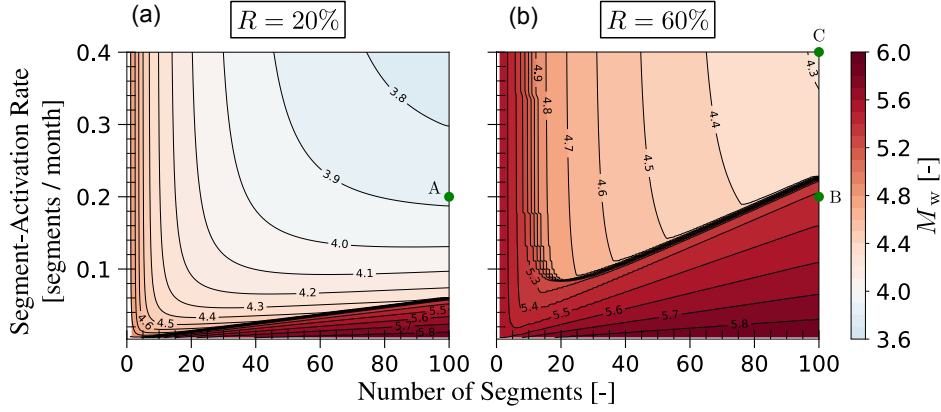


Figure 4. The maximum magnitude is plotted in function of the segment-activation rate, number of fault segments and two different stress levels, based on our fault scenario: (a) $R = 20\%$ and (b) $R = 60\%$.

244 model, this rate has to be fast enough to outpace the progressive energy build-up due
 245 to the far-field tectonic displacements. When our segment-activation rate is fast enough,
 246 the system releases its internal energy and the large event is avoided. It seems that this
 247 is the case in many industrial projects that involve injections of large amounts of fluids
 248 in the earth's crust (McGarr, 2014; Guglielmi et al., 2015; Grigoli et al., 2018).

249 According to Hosseini et al. (2018), fluid boundary conditions play an important
 250 role in induced seismicity. In our experimental work, fluid boundary conditions are expressed
 251 through segmentation by adjusting plastic (impermeable) barriers between the stripes
 252 (see also supporting information §4). Each injection leads to only one seismic event resulting
 253 in a linear relation between the number of cumulative events in the fault and the time,
 254 presuming constant segment-activation rate. Eventually, the number of segments, that
 255 a fault has been divided into, depicts the maximum number of stimulated events.

256 In the absence of impermeable barriers, high number of segments would represent
 257 better the physical reality, where the distribution of injection pressure does not occur
 258 instantly over a region (paper segment), but follows a diffusion process (Bhattacharya
 259 & Viesca, 2019). The diffusion process due to fluid injection in faults is equivalent to the
 260 progressive wetting of paper stripes. If we assume, for instance, a high-permeable damage
 261 fault zone with hydraulic diffusivity of the surrounding rocks of the order of 10^{-1} to 10^1 m²/s
 262 (values taken from Lim et al., 2020), the time it takes for each segment (1.3×6.5 km²)
 263 to be saturated after fluid injection ranges between 10 to 980 days, respectively. In Figure
 264 3a, where the experimental results of the proposed injection strategy are presented, the
 265 segment-activation rate is 3 stripes/min which corresponds to 0.01 segments/month in
 266 a real case scenario. Therefore, the above evaluated diffusion time is sufficient enough
 267 in order to assure fast saturation of each segment.

268 Figure 4 presents the computed magnitude of the maximum earthquake event that
 269 would occur, as a function of segment-activation rate and number of segments. For instance,
 270 under a given rate of one injection per five months and for $R = 20\%$, one obtains a maximum
 271 $M_w \approx 3.9$, when segmenting the fault into 100 parts (point A, Figure 4a). For $R =$
 272 60% , though, the injection program leads to a large event of $M_w \approx 5.4$, close to the
 273 natural one of $M_w \approx 5.9$ (point B, Figure 4b). Doubling the rate from one to two injections
 274 per five months reduces the maximum event to $M_w \approx 4.3$ (point C, Figure 4b).

275 Despite the numerous uncertainties in the properties of the earth's crust (Cornet,
 276 2019), our experiments (Figure 3c) and model (Figure 4) reveal the strong dependency
 277 between the outcome of the injection strategy and the three aforementioned key parameters
 278 (initial stress level, segment-activation rate and segmentation). By adequately controlling
 279 these parameters, we managed to artificially reduce the stored elastic energy in an analogue
 280 tectonic fault. However, in practice these parameters are hard to control and other strategies
 281 based on the mathematical theory of control could provide rigorous alternatives (Stefanou,
 282 2019, 2020).

283 Data Availability Statement

284 The raw data from all the performed experiments of this study are publicly available in
 285 Zenodo repository in Tzortzopoulos et al. (2020).

286 Acknowledgments

287 Funding: This work was supported by the European Research Council (ERC) under the
 288 European Union Horizon 2020 research and innovation program (Grant agreement no.
 289 757848 CoQuake), <http://coquake.com>.

290 Contribution: All authors contributed to the analysis and writing the manuscript.

291 Competing interests: The authors declare that they have no competing interests.

292 The authors thank Prof. I. Einav for his fruitful comments and our scientific discussions.

293 The authors also would like to thank Dr. Pierrick Guégan for his help in the preparation
 294 and calibration of the traction apparatus in the laboratory.

295 References

- 296 Bhattacharya, P., & Viesca, R. C. (2019). Fluid-induced aseismic fault slip
 297 outpaces pore-fluid migration. *Science*, *364*(6439), 464–468. Retrieved
 298 from <https://science.sciencemag.org/content/364/6439/464> doi:
 299 10.1126/science.aaw7354
- 300 Birkeland, K. W., & Landry, C. C. (2002). Power-laws and snow avalanches.
 301 *Geophysical Research Letters*, *29*(11), 49-1-49-3. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001GL014623)
 302 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001GL014623 doi:
 303 10.1029/2001GL014623
- 304 Bommer, J. J., Oates, S., Cepeda, J. M., Lindholm, C., Bird, J., Torres, R., ...
 305 Rivas, J. (2006). Control of hazard due to seismicity induced by a hot
 306 fractured rock geothermal project. *Engineering Geology*, *83*(4), 287 - 306.
 307 Retrieved from [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S0013795205003108)
 308 [S0013795205003108](http://www.sciencedirect.com/science/article/pii/S0013795205003108) doi: <https://doi.org/10.1016/j.enggeo.2005.11.002>
- 309 Cappa, F., Scuderi, M. M., Collettini, C., Guglielmi, Y., & Avouac, J.-P. (2019).
 310 Stabilization of fault slip by fluid injection in the laboratory and in situ.
 311 *Science Advances*, *5*(3). Retrieved from [https://advances.sciencemag.org/](https://advances.sciencemag.org/content/5/3/eaau4065)
 312 [content/5/3/eaau4065](https://advances.sciencemag.org/content/5/3/eaau4065) doi: 10.1126/sciadv.aau4065
- 313 Cornet, F. H. (2019). The engineering of safe hydraulic stimulations for egs
 314 development in hot crystalline rock masses. *Geomechanics for Energy and*
 315 *the Environment*, 100151. Retrieved from [http://www.sciencedirect.com/](http://www.sciencedirect.com/science/article/pii/S2352380819300280)
 316 [science/article/pii/S2352380819300280](http://www.sciencedirect.com/science/article/pii/S2352380819300280) doi: [https://doi.org/10.1016/](https://doi.org/10.1016/j.gete.2019.100151)
 317 [j.gete.2019.100151](https://doi.org/10.1016/j.gete.2019.100151)
- 318 Dieterich, J. H. (1979). Modeling of rock friction: 1. experimental results and
 319 constitutive equations. *Journal of Geophysical Research: Solid Earth*, *84*(B5),
 320 2161-2168. Retrieved from [https://agupubs.onlinelibrary.wiley.com/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB084iB05p02161)
 321 [doi/abs/10.1029/JB084iB05p02161](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JB084iB05p02161) doi: 10.1029/JB084iB05p02161
- 322 Edwards, B., Kraft, T., Cauzzi, C., Kästli, P., & Wiemer, S. (2015). Seismic
 323 monitoring and analysis of deep geothermal projects in St Gallen and Basel,

- 324 Switzerland. *Geophysical Journal International*, 201(2), 1022-1039. Retrieved
 325 from <https://doi.org/10.1093/gji/ggv059> doi: 10.1093/gji/ggv059
- 326 Einav, I., & Guillard, F. (2018). Tracking time with ricequakes in partially
 327 soaked brittle porous media. *Science Advances*, 4(10). Retrieved from
 328 <https://advances.sciencemag.org/content/4/10/eaat6961> doi:
 329 10.1126/sciadv.aat6961
- 330 Ellsworth, W. L. (2013). Injection-induced earthquakes. *Science*, 341(6142).
 331 Retrieved from [https://science.sciencemag.org/content/341/6142/](https://science.sciencemag.org/content/341/6142/1225942)
 332 1225942 doi: 10.1126/science.1225942
- 333 Foulger, G. R., Wilson, M. P., Gluyas, J. G., Julian, B. R., & Davies, R. J.
 334 (2018). Global review of human-induced earthquakes. *Earth-Science*
 335 *Reviews*, 178, 438 - 514. Retrieved from [http://www.sciencedirect.com/](http://www.sciencedirect.com/science/article/pii/S001282521730003X)
 336 [science/article/pii/S001282521730003X](http://www.sciencedirect.com/science/article/pii/S001282521730003X) doi: [https://doi.org/10.1016/](https://doi.org/10.1016/j.earscirev.2017.07.008)
 337 [j.earscirev.2017.07.008](https://doi.org/10.1016/j.earscirev.2017.07.008)
- 338 Garagash, D. I., & Germanovich, L. N. (2012). Nucleation and arrest of dynamic
 339 slip on a pressurized fault. *Journal of Geophysical Research: Solid Earth*,
 340 117(B10). Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2012JB009209)
 341 [abs/10.1029/2012JB009209](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2012JB009209) doi: 10.1029/2012JB009209
- 342 Grigoli, F., Cesca, S., Rinaldi, A. P., Manconi, A., López-Comino, J. A., Clinton,
 343 J. F., ... Wiemer, S. (2018). The november 2017 mw 5.5 pohang earthquake:
 344 A possible case of induced seismicity in south korea. *Science*, 360(6392), 1003–
 345 1006. Retrieved from [https://science.sciencemag.org/content/360/6392/](https://science.sciencemag.org/content/360/6392/1003)
 346 1003 doi: 10.1126/science.aat2010
- 347 Guglielmi, Y., Cappa, F., Avouac, J.-P., Henry, P., & Elsworth, D. (2015).
 348 Seismicity triggered by fluid injection–induced aseismic slip. *Science*,
 349 348(6240), 1224–1226. Retrieved from [https://science.sciencemag.org/](https://science.sciencemag.org/content/348/6240/1224)
 350 [content/348/6240/1224](https://science.sciencemag.org/content/348/6240/1224) doi: 10.1126/science.aab0476
- 351 Gupta, H. K. (2002). A review of recent studies of triggered earthquakes by
 352 artificial water reservoirs with special emphasis on earthquakes in koyna,
 353 india. *Earth-Science Reviews*, 58(3), 279 - 310. Retrieved from [http://](http://www.sciencedirect.com/science/article/pii/S0012825202000636)
 354 www.sciencedirect.com/science/article/pii/S0012825202000636 doi:
 355 [https://doi.org/10.1016/S0012-8252\(02\)00063-6](https://doi.org/10.1016/S0012-8252(02)00063-6)
- 356 Gutenberg, B., & Richter, C. F. (1954). *Seismicity of the earth and associated*
 357 *phenomena* (2nd ed.). Princeton University Press, Princeton, N. J.
- 358 Hamilton, R. M., Smith, B. E., Fischer, F. G., & Papanek, P. J. (1972).
 359 Earthquakes caused by underground nuclear explosions on pahute mesa,
 360 nevada test site. *Bulletin of the Seismological Society of America*, 62(5),
 361 1319-1341.
- 362 Harris, R. A. (1998). Introduction to special section: Stress triggers, stress
 363 shadows, and implications for seismic hazard. *Journal of Geophysical*
 364 *Research: Solid Earth*, 103(B10), 24347-24358. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/98JB01576)
 365 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/98JB01576 doi:
 366 10.1029/98JB01576
- 367 Heslot, F., Baumberger, T., Perrin, B., Caroli, B., & Caroli, C. (1994). Creep, stick-
 368 slip, and dry-friction dynamics: Experiments and a heuristic model. *Phys. Rev.*
 369 *E*, 49, 4973–4988. Retrieved from [https://link.aps.org/doi/10.1103/](https://link.aps.org/doi/10.1103/PhysRevE.49.4973)
 370 [PhysRevE.49.4973](https://link.aps.org/doi/10.1103/PhysRevE.49.4973) doi: 10.1103/PhysRevE.49.4973
- 371 Hosseini, S. M., Goebel, T. H. W., Jha, B., & Aminzadeh, F. (2018). A probabilistic
 372 approach to injection-induced seismicity assessment in the presence and
 373 absence of flow boundaries. *Geophysical Research Letters*, 45(16), 8182-
 374 8189. Retrieved from [https://agupubs.onlinelibrary.wiley.com/doi/abs/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL077552)
 375 [10.1029/2018GL077552](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL077552) doi: 10.1029/2018GL077552
- 376 Kanamori, H., & Brodsky, E. E. (2004). The physics of earthquakes. *Reports on*
 377 *Progress in Physics*, 67(8), 1429–1496. Retrieved from [https://doi.org/10](https://doi.org/10.1088/0034-4885/67/8/r03)
 378 [.1088/0034-4885/67/8/r03](https://doi.org/10.1088/0034-4885/67/8/r03) doi: 10.1088/0034-4885/67/8/r03

- 379 King, C.-Y. (1975). Model seismicity and faulting parameters. *Bulletin of the*
 380 *Seismological Society of America*, 65(1), 245-259.
- 381 Knuth, M., & Marone, C. (2007). Friction of sheared granular layers: Role
 382 of particle dimensionality, surface roughness, and material properties.
 383 *Geochemistry, Geophysics, Geosystems*, 8(3). Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006GC001327)
 384 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006GC001327 doi:
 385 10.1029/2006GC001327
- 386 Latour, S., Voisin, C., Renard, F., Larose, E., Catheline, S., & Campillo, M. (2013).
 387 Effect of fault heterogeneity on rupture dynamics: An experimental approach
 388 using ultrafast ultrasonic imaging. *Journal of Geophysical Research: Solid*
 389 *Earth*, 118(11), 5888-5902. Retrieved from [https://agupubs.onlinelibrary](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JB010231)
 390 [.wiley.com/doi/abs/10.1002/2013JB010231](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JB010231) doi: 10.1002/2013JB010231
- 391 Li, T., Cai, M., & Cai, M. (2007). A review of mining-induced seismicity in china.
 392 *International Journal of Rock Mechanics and Mining Sciences*, 44(8), 1149 -
 393 1171. Retrieved from [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S1365160907000810)
 394 [pii/S1365160907000810](http://www.sciencedirect.com/science/article/pii/S1365160907000810) doi: <https://doi.org/10.1016/j.ijrmms.2007.06.002>
- 395 Lim, H., Deng, K., Kim, Y., Ree, J.-H., Song, T.-R. A., & Kim, K.-H. (2020).
 396 The 2017 mw 5.5 pohang earthquake, south korea, and poroelastic
 397 stress changes associated with fluid injection. *Journal of Geophysical*
 398 *Research: Solid Earth*, 125(6), e2019JB019134. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB019134)
 399 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB019134
 400 (e2019JB019134 2019JB019134) doi: 10.1029/2019JB019134
- 401 Lockner, D. A., Byerlee, J. D., Kuksenko, V., Ponomarev, A., & Sidorin, A. (1991).
 402 Quasi-static fault growth and shear fracture energy in granite. *Nature*,
 403 350(6313), 39-42. Retrieved from <https://doi.org/10.1038/350039a0>
 404 doi: 10.1038/350039a0
- 405 McGarr, A. (2014). Maximum magnitude earthquakes induced by fluid injection.
 406 *Journal of Geophysical Research: Solid Earth*, 119(2), 1008-1019. Retrieved
 407 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JB010597)
 408 [2013JB010597](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JB010597) doi: 10.1002/2013JB010597
- 409 McGarr, A., Simpson, D., & Seeber, L. (2002). 40 - case histories of induced
 410 and triggered seismicity. In W. H. Lee, H. Kanamori, P. C. Jennings, &
 411 C. Kisslinger (Eds.), *International handbook of earthquake and engineering*
 412 *seismology, part a* (Vol. 81, p. 647 - 661). Academic Press. Retrieved from
 413 <http://www.sciencedirect.com/science/article/pii/S0074614202802431>
 414 doi: [https://doi.org/10.1016/S0074-6142\(02\)80243-1](https://doi.org/10.1016/S0074-6142(02)80243-1)
- 415 Nussbaum, J., & Ruina, A. (1987). A two degree-of-freedom earthquake model
 416 with static/dynamic friction. *Pure and Applied Geophysics*, 125(4), 629-656.
 417 Retrieved from <http://link.springer.com/10.1007/BF00879576> doi:
 418 10.1007/BF00879576
- 419 Pluijm, van der, R. (1999). *Out-of-plane bending of masonry : behaviour and*
 420 *strength* (Doctoral dissertation, Department of the Built Environment).
 421 (Proefschrift.) doi: 10.6100/IR528212
- 422 Popov, V., Grzempa, B., Starcevic, J., & Popov, M. (2012). Rate and state
 423 dependent friction laws and the prediction of earthquakes: What can we learn
 424 from laboratory models? *Tectonophysics*, 532-535, 291 - 300. Retrieved from
 425 <http://www.sciencedirect.com/science/article/pii/S0040195112001138>
 426 doi: <https://doi.org/10.1016/j.tecto.2012.02.020>
- 427 Raleigh, C. B., Healy, J. H., & Bredehoeft, J. D. (1976). An experiment in
 428 earthquake control at Rangely, Colorado. *Science*, 191(4233), 1230-1237.
 429 Retrieved from <https://science.sciencemag.org/content/191/4233/1230>
 430 doi: 10.1126/science.191.4233.1230
- 431 Reid, H. F. (1910). The Mechanics of the Earthquake, The California Earthquake of
 432 April 18, 1906. In *Report of the state earthquake investigation commission, vol.*
 433 *2*. Washington, D. C.: Carnegie Institution of Washington.

- 434 Rosenau, M., Corbi, F., & Dominguez, S. (2017). Analogue earthquakes and seismic
 435 cycles: experimental modelling across timescales. *Solid Earth*, 8(3), 597–635.
 436 Retrieved from <https://www.solid-earth.net/8/597/2017/> doi: 10.5194/se
 437 -8-597-2017
- 438 Rubinstein, J. L., & Mahani, A. B. (2015). Myths and Facts on Wastewater
 439 Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced
 440 Seismicity. *Seismological Research Letters*, 86(4), 1060-1067. Retrieved
 441 from <https://doi.org/10.1785/0220150067> doi: 10.1785/0220150067
- 442 Scholz, C. H. (2002). *The mechanics of earthquakes and faulting* (2nd ed.).
 443 Cambridge University Press. doi: 10.1017/CBO9780511818516
- 444 Schultz, R., Skoumal, R. J., Brudzinski, M. R., Eaton, D., Baptie, B., & Ellsworth,
 445 W. (2020). Hydraulic fracturing-induced seismicity. *Reviews of Geophysics*,
 446 58(3), e2019RG000695. Retrieved from [https://agupubs.onlinelibrary](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019RG000695)
 447 [.wiley.com/doi/abs/10.1029/2019RG000695](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019RG000695) (e2019RG000695
 448 2019RG000695) doi: 10.1029/2019RG000695
- 449 Scuderi, M., Collettini, C., Viti, C., Tinti, E., & Marone, C. (2017). Evolution
 450 of shear fabric in granular fault gouge from stable sliding to stick slip and
 451 implications for fault slip mode. *Geology*, 45(8), 731-734. Retrieved from
 452 <https://doi.org/10.1130/G39033.1> doi: 10.1130/G39033.1
- 453 Shapiro, S. A., Krüger, O. S., & Dinske, C. (2013). Probability of inducing given-
 454 magnitude earthquakes by perturbing finite volumes of rocks. *Journal of*
 455 *Geophysical Research: Solid Earth*, 118(7), 3557-3575. Retrieved from
 456 <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgrb.50264>
 457 doi: 10.1002/jgrb.50264
- 458 Stefanou, I. (2019). Controlling anthropogenic and natural seismicity: Insights
 459 from active stabilization of the spring-slider model. *Journal of Geophysical*
 460 *Research: Solid Earth*, 124(8), 8786-8802. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB017847)
 461 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB017847 doi:
 462 10.1029/2019JB017847
- 463 Stefanou, I. (2020). Control instabilities and incite slow-slip in generalized burridge-
 464 knopoff models. *arXiv:2008.03755*.
- 465 Tzortzopoulos, G., Braun, P., & Stefanou, I. (2020, dec). *Paper-Quake Mitigation*
 466 *Strategy: Experimental Raw Data*. Zenodo. Retrieved from [https://doi.org/](https://doi.org/10.5281/zenodo.4380988)
 467 [10.5281/zenodo.4380988](https://doi.org/10.5281/zenodo.4380988) doi: 10.5281/zenodo.4380988
- 468 van der Elst, N. J., Page, M. T., Weiser, D. A., Goebel, T. H., & Hosseini, S. M.
 469 (2016). Induced earthquake magnitudes are as large as (statistically) expected.
 470 *Journal of Geophysical Research: Solid Earth*, 121(6), 4575-4590. Retrieved
 471 from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JB012818)
 472 [2016JB012818](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JB012818) doi: 10.1002/2016JB012818