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On the controversial role of earthquake triggering of the Rigopiano avalanche

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Here Nicola Pugno, leading expert in fracture mechanics, deduces by sticking to the facts that (1) there is no evidence of earthquake triggering of the Rigopiano avalanche, (2) earthquake triggering of this avalanche is very unlikely, (3) even if it cannot be proved nor disproved, (4) those earthquakes are equivalent to only a few centimeters of snow precipitation, and (5) even assuming earthquake triggering, the avalanche would have likely occurred the very same day even in absence of earthquakes.

On January 18, 2017, an avalanche destroyed a tourist facility in Rigopiano, Italy, killing 29 people and injuring 11 others. Today, after 5 years, a fundamental question remains open regarding the potential role in avalanche triggering of the numerous earthquakes recorded in that central region of Italy on the same day (more than 30 min before the avalanche release).

Science has developed great understanding of the materials that compose it, utilizing knowledge of chemistry, physics, and mechanics to predict materials failure, for example. Science has also amassed great understanding of natural phenomena at the grandest scale, including earthquakes, hurricanes, and tsunamis, to name a few destructive examples. However, the full understanding of such phenomena is a complex task due to the related uncertainties, common to nearly all such periodic destructive events. The dramatic Rigopiano avalanche that took place 5 years ago (Figure 1A) is no exception. Can we turn to our knowledge of mechanics of materials for answers?

Fracture mechanics was established 100 years ago in 1921 by Griffith to predict crack propagation and the related fracture stress or strength of real, thus defective, materials. Accordingly, we developed a fracture mechanics avalanche theory that is able to unify and generalize all the main previous avalanche fracture models (as well as failure of seracs/snow frames and other important causes of avalanche), as discussed by Pugno.[1] It considers a (super weakest) defect or crack of length $2a$ in the sliding (weakest) interface and an upper snow slab of vertical height H and thus thickness $h = H\cos\theta$ on a slope with inclination θ, as shown in Figure 1B. Avalanche release/crack propagation takes place when the so-called energy release rate (the opposite of the variation of the total potential energy, i.e., the elastic energy minus the external work, with respect to the crack surface area) reaches the fracture energy (per unit area) of the interface. In terms of stress, this is equivalent to crack propagation occurring when the applied shear stress τ_N reaches the total snow resistance τ_R, the sum of the cohesion/adhesion resistance (or in general a constant residual term) τ_a, the friction resistance (governed by f, the friction coefficient at the sliding interface) τ_f, and the fracture resistance (governed by G_C, the mode II fracture energy of the interface) τ_F—i.e., fracture takes place when $\tau_N = \tau_R = \tau_a + \tau_f + \tau_F$. The expressions for these different terms are provided by Pugno[1] and reported in Figure 1B, where we have also added the seismic acceleration terms (see below) and assumed negligible the discrete crack advancement,[1] as in classical continuous fracture models. These expressions emerge from a trivial force equilibrium and a non-trivial energy balance.[1]

In Piacentini et al.,[2] the trigger of the avalanche is analytically investigated, basically assuming a simplified version of the previous model, considering a constant shear resistance τ_R, i.e., formally within our context with $f = G_C = 0$ and $\tau_R = \tau_a$ = const. Following previous literature, these authors[2] also investigated the role of an earthquake adding the slope-parallel component of the local seismic ground acceleration $A_{//}(t)$ to the related component of the acceleration of gravity $g\sin\theta$ in τ_N and then substituting the time-dependent acceleration with the local seismic peak ground acceleration $A_{//}$ (conservatively rescaling the measured value to take into account local acceleration concentrations), i.e., $\tau_N = \rho h(g\sin\theta + A_{//})$ (Figure 1B), where the sign is conservatively assumed to be positive (i.e., seismic acceleration increases the gravitational component). This approach is used in Piacentini et al.[2] for treating the 5 nearest earthquakes (their Table 5) in space and time to the Rigopiano avalanche, even though they did not coincide with the avalanche release (considered in Piacentini et al.[2] at 16:48 CET, estimated at 16:41:59 CET, and impacting the Rigopiano hotel at 16:43:20

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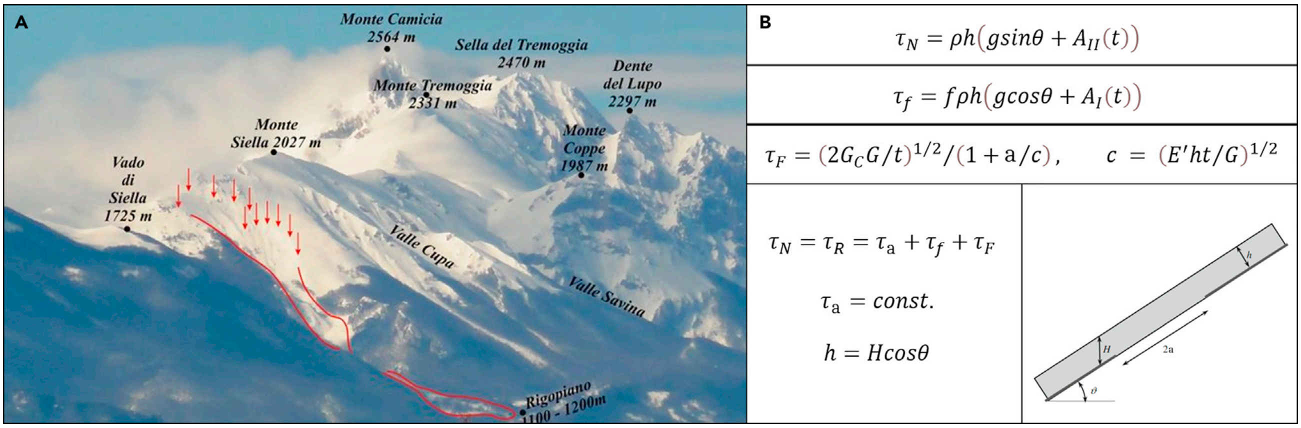

Figure 1. Rigopiano avalanche release region at about 1800 m of altitude (left) and fracture mechanics model (right)

(A) Rigopiano avalanche release region (photo from https://www.rete8.it/cronaca/67890hotel-rigopiano-confermato-era-in-zona-valanga/).

(B) Avalanche geometrical model and expressions for the applied shear stress, resistance shear strengths, and final condition for the crack propagation/avalanche triggering. ρ is the (mean) snow density of the upper (with respect to the weakest/sliding interface) snow slab; g is the acceleration of gravity; E and v are the snow Young's modulus and Poisson's ratio of this slab, respectively, $E' = E/(1 - v^2)$; f is the friction coefficient at the sliding interface; and G_C is the mode II fracture energy (per unit area) of the sliding interface of thickness t and shear elastic modulus G ($2a$ is the crack length; H is the snow slab vertical height over the sliding interface; and $h = Hcos\theta$ is its thickness, on a slope with an inclination θ). $A_{II}(t)$ or $A_I(t)$ are the slope-parallel or -perpendicular local components of the seismic ground acceleration, to be considered only in the presence of a concurrent earthquake (the material properties could significantly change in time, e.g., G_C with strain-rate, temperature, and wind, also affecting snow properties and accumulations and thus H).

in Braun et al.[3]). This basically implies assuming the earthquakes as "concurrent" with the avalanche release, resulting in the predictions reported in their table "Stability index calculation for the main January 18, 2017 earthquakes."[2] (Note 1: In their table,[2] the second column reports ρgh in kg/m^2, suggesting that in reality ρh is reported in this column; however, the values are 10 times smaller than real ones. The same wrong physical unit is reported in column 5. However, the last column and thus final arguments are not affected. We do not comment on the simulations reported in Piacentini et al.[2] based on several assumptions.) The Stability index in Piacentini et al.[2] is accordingly defined as $S = \tau_R/\tau_N = \tau_R/(\rho h(gsin\theta + A_{II}))$, and the avalanche is released when S becomes equal to or smaller than 1. In Piacentini et al.[2] the following conclusion is reached: "From this analysis, we established, with weighted certainty, that as a result of the seismic shocks, a snow depth greater than ~1.3 m over the sliding plane could have triggered the avalanche release (red values in Table 5). This corresponds to what occurred in the Rigopiano valley, except for the delayed trigger." In the same paper,[2] Puzrin et al.[4] is invoked (a new theory with the key ingredient of a shear strength hardening-softening strain-rate dependence) to justify the delayed trigger. Note that the last of these earthquakes, the nearest in time (reported in Piacentini et al.[2] as taking place 32 min before the avalanche and with a magnitude M = 4.3, as we will assume here, although it is not essential), is the only one fitted in Puzrin et al. (reported as taking place about 40 min before the avalanche and with M = 4.6).[4]

Considering the local seismic peak ground accelerations $A_{I,II}$ and for a concurrent earthquake $A_{II}(t) = A_{II}$ and $A_I(t) = -A_I$ could be considered in the related stresses evaluations (very conservatively, since we are considering the peak values of the two local acceleration components as concurrent as well as increasing the applied load and decreasing the friction resistance).

First, we note that following this approach of Piacentini et al.,[2] any arbitrarily small earthquake or even minute vibration could be established as the cause of avalanche triggering: it is sufficient to assume the snow slab thickness h over the weakest interface to be close enough to its critical value for crack propagation h_C that would emerge in the absence of the earthquake. In formulae, following Piacentini et al.,[2] this happens for $S = 1$ and thus:

$$h = h_C/(1 + A_{II}/(gsin\theta)) \qquad \text{(Equation 1)}$$

Accordingly, the statement that "this corresponds to what occurred in the Rigopiano valley, except for the delayed trigger," is not supported by data in Piacentini et al.[2]

Second, the effect of an earthquake could in principle be postponed in time by a natural mechanism of stable crack propagation, increasing the crack length a without propagating the avalanche but reducing the fracture strength (τ_F). This possibility is very unlikely for avalanche release, since the predicted crack propagation is unstable (τ_F is reduced by increasing the crack length a; see related expression in Figure 1B). (Note 2: This situation is similar to a crack in a sheet of paper tractioned by our hands at the borders of the sheet: we are unable to propagate the crack in a stable manner and thus stop it before the complete failure of the sheet into two pieces, which is indeed theoretically impossible. Note that also the friction strength is in principle reduced after crack propagation, since the static friction coefficient is larger than the dynamic one.) A stable crack propagation would need to invoke other very unlikely mechanisms such as heterogenous regions weakly stabilizing the unstable shear mode II crack propagation, for which we have no evidence in the Rigopiano avalanche. This would be less very unlikely for a crack length $a << c$, i.e., when τ_F is nearly constant (see definition of characteristic length c in Figure 1B).

Third, note that the theory proposed in Puzrin et al.[4] starts from the strong assumption that an earthquake is generating an initial crack of length $a_0 > a_g = c/k$, where k is a numerical prefactor (of the order of $\tan\theta/f - 1$) but smaller than the critical value for crack propagation (deducible here by determining a_C from $\tau_N = \tau_R = \tau_a + \tau_f + \tau_F(a_C/c)$). As mentioned, this is very unlikely, although of course not impossible, for this shear mode II crack propagation (and also for mode I) since the process is theoretically unstable. (Note 3: Theoretically, for mode I crack propagation generated by an earthquake, we need a traction in the snow, thus $A_I - g\cos\theta > 0$. Mode I crack propagation thus requires in principle a large acceleration A_I [for plausible inclinations] and in addition remains unstable or weakly unstable for $a << L$ with L size of the slope, as we have verified. In contrast, a localized applied force, such as that generated by a skier or by a localized explosion under particular circumstances [and even an earthquake perhaps in some very particular circumstances, as assumed in Puzrin et al.[4]] could generate a stable crack. In the previous analogy, this is equivalent to the stable crack propagation in a sheet of paper tractioned by our hands directly at the borders of the crack). In any case, any observed time delay T_D, even an arbitrarily large one, could be fitted with the theory proposed in Puzrin et al.[4] considering the arbitrary assumed a_0 sufficiently close to a_g, since the theory predicts that T_D tends to infinity for a_0 tending to a_g. In formulae, following Puzrin et al.,[4] this happens for the arbitrary value of a_0 satisfying:

$$T_D = t_r \ln(a_0/(a_0 - a_g)) + t_r/k \ln((a_C - a_g)/(a_0 - a_g)), \quad \text{(Equation 2)}$$

where t_r is a characteristic relaxation time.[4] Accordingly, the Rigopiano case reported in Puzrin et al.[4] must only be considered as a fitting example (as was probably the intention of these authors).

In summary, there is no evidence of earthquake triggering for the Rigopiano avalanche in both Piacentini et al.[2] and Puzrin et al.,[4] and the unstable crack propagation predicted by the well-established fracture mechanics suggests that this scenario is very unlikely.

Also, we note that concurrent earthquakes could also affect the friction resistance τ_f; similarly to the previous argument, we expect $\tau_f = f\rho h(g\cos\theta + A_I(t)) > 0$, with $A_I(t)$ as the slope-perpendicular component of the local seismic ground acceleration. Substituting the time-dependent acceleration with the local seismic peak ground acceleration A_I, we have $\tau_f = f\rho h(g\cos\theta - A_I)$, where the minus sign is conservatively assumed (seismic acceleration decreases the frictional resistance). Thus, a concurrent earthquake not only increases the applied load (τ_N) but also reduces the friction resistance (τ_f).

Moreover, without the exact knowledge of the snow material properties, unknown for the Rigopiano avalanche, the earthquake triggering cannot be proven nor disproven, as confirmed by the opposite deductions reported in Piacentini et al.[2] and Chiaia et al.[5] by slightly changing unknown parameters in their plausible ranges and approaches. (Note 4: Considering plausible values of τ_R = 1–2 kPa, ρ = 100–200 kg/m^3 and $\theta = 35^\circ$ results in h = 0.89–3.55 m.) We thus prefer to stick to the facts as far as possible with the following considerations.

To compare two quantities, these must have the same physical units. In our context, this could be translated in the following fundamental question: which is the snow height increment $\Delta H = H' - H$ equivalent to a given earthquake?

To answer this question, we pose the equivalence in terms of net shear stress, i.e., $\tau_N(H,A_{II}) - \tau_f(H,A_I) - \tau_F(H) = \tau_N(H',A_{II} = 0) - \tau_f(H',A_I = 0) - \tau_F(H')$. Note that since τ_a = const., if H is critical (i.e., satisfies $\tau_N = \tau_R$), H' is also critical. For the previously mentioned reason, we consider here τ_F = const. (thus $a << c$, or more in general $a \propto c$; note that for $a >> c$, where crack propagation is strongly unstable, a quadratic form and thus still a closed-form solution would emerge). Accordingly, we find the following fundamental answer that is nearly (apart from friction) independent of (unknown) material properties and thus quite robust and useful:

$$\Delta H/H = (A_{II} + fA_I)/(g(\sin\theta - f\cos\theta)) \quad \text{(Equation 3)}$$

Now let us accept *in toto* the approach of Piacentini et al.,[2] thus formally $f = 0$ and simply $\Delta H/H = A_{II}/(g\sin\theta)$. We consider the data reported in Piacentini et al.,[2] i.e., the earthquake is as concurrent and triggers the avalanche at H_C = 1.587 m (h = 1.3 m in their table), $\theta = 35^\circ$, and A_{II} = 11.384, 20.130, 17.540, 10.713, or 3.520 cm/s^2 (from their rescaled values reported in the table). These last values correspond to the 5 mentioned earthquakes, E1–5, respectively: earthquake E1 (Magnitude M = 5.1, 10:25 CET, i.e., T = 383 min before the event), E2

(M = 5.5, 11:14 CET, T = 334 min), E3 (M = 5.4, 11:25 CET, T = 323 min), E4 (M = 5.0, 14:33 CET, T = 135 min), or E5 (M = 4.3, 16:16 CET, T = 32 min; assumed here—as already mentioned and not essential—as in Piacentini et al., avalanche release also assumed here at 16:48 CET[2]). Accordingly, for E1–5 we find that the earthquakes are equivalent to ΔH = 3.21, 5.68, 4.95, 3.02, or 0.99 cm, respectively. Having ascertained—as demonstrated by this analysis—that these earthquakes are in terms of overload equivalent to a few centimeters of fresh snow and that about 3 m (from MeteoBlue[5]) of fresh snow fell in the 72 h just before the avalanche, it is evident that the effect of these earthquakes was—regardless of any other consideration—negligible compared to the very predictable effect, in progress, of the snow itself. Note that after the Rigopiano avalanche, there was a snow fall for about 135 min at a rate of about 4.5 cm/h (from MeteoBlue[5]), corresponding to approximately 10.125 cm. Accordingly, even assuming that one of these earthquakes triggered the Rigopiano avalanche, its release would have been expected the very same day even in absence of earthquakes, i.e., Δt = 42.8, 75.7, 66.0, 40.3, or 13.2 min later, respectively. This scenario, deduced according to Piacentini et al.,[2] does not change significantly considering an intermediate or maximal friction coefficient (or even for $a >> c$). (Note 5: We consider the case of a friction coefficient of $f = 0.2$ [with H_C, θ and A_{II} as before[2]]. For $A_I = 0$, we find for E1–5 ΔH = 4.49, 7.95, 6.93, 4.23, or 1.39 cm, respectively, corresponding to Δt = 59.9, 106.0, 92.3, 56.4, or 18.5 min, respectively [and this scenario does not change qualitatively up to a friction coefficient of 0.30, otherwise it becomes similar to the case of maximal friction]. As another representative scenario, we consider $A_I = A_{II}$ and find respectively for E1–5 ΔH = 5.39, 9.54, 8.31, 5.08, or 1.67 cm, corresponding to Δt = 71.9, 127.2, 110.8, 67.7, or 22.2 min, respectively [and this scenario does not change qualitatively up to a friction coefficient of 0.22, otherwise it becomes similar to the case of maximal friction]. In both cases the situation is similar to the case treated according to Piacentini et al.,[2] since ΔH < 10.125 cm for all the earthquakes.

We also consider a limiting scenario, i.e., with maximal friction [with H_C, θ and A_{II} as before[2]]. The friction coefficient is unknown, but its maximal value can be estimated noting that the avalanche was not released during any of the earthquakes E1–5. Let us call H_E the value of H at the instant of a given earthquake. Since the avalanche was not triggered during the earthquake, $H' < H_C$ and the maximal friction can be estimated from the limiting condition $H' = H_C$, i.e., posing $(H_C - H_E)/H_E = \Delta H(f)/H$ in Equation 3 and deducing f for each earthquake. During the earthquake-avalanche intervals T, we had for E1–5 about $H_C - H_E$ = 21, 20, 19, 10, or 2 cm of snowfall, respectively [from MeteoBlue[5]]. From these data we find a maximal value for f, and thus the real one is the minimal value. For $A_I = 0$, we deduce f_{max} = 0.357 [imposed by E5] and find for E1–5 upper bounds of ΔH = 6.55, 11.58, 10.09, 6.16, or 2.03 cm, respectively, corresponding to Δt = 87.3, >135, 134.6, 82.2, or 27.0 min, respectively. For $A_I = A_{II}$, we similarly find f_{max} = 0.266 [again imposed by E5] and upper bounds of ΔH = 6.56, 11.59, 10.10, 6.17, or 2.03 cm, corresponding to Δt = 87.4, >135, 134.7, 82.2, or 27.0 min, respectively.

This limiting scenario is the same that would also emerge for $a >> c$ and thus $\tau_F \cong (2E' G_C H cos\theta)^{1/2}/a$ and $\tau_R \cong \tau_F$, for which we find $\Delta H/H \cong (1 + A_{II}/(g sin\theta))^2 - 1$, and for E1–5, respectively, about ΔH = 6.49, 11.56, 10.05, 6.10, or 1.99 cm, corresponding to Δt = 86.5, >135, 134.0, 81.3, or 26.6 min, respectively.)

Note that the presence of a weak interface with snow pellets (see Video S1 on this peculiar type of snow) of about 2 cm in thickness was observed for the Rigopiano avalanche and deduced (from MeteoBlue data[5]) at a value of H from the surface of about 2.13 m over a total height of 3.10 m, or, experimentally,[5] on 20 January in the Rigopiano zone (at about 1100 m of altitude, by the Meteomont service[5]) at a value of 1.22 m from the surface over a total height of 1.97 m with a thickness of about 1 cm; also, experimentally, on 22 January near the zone of the avalanche release (at about 1600 m of altitude, again by the Meteomont service[5]), a weakest interface was demonstrated with an *in situ* stability test at about 1.5 m from the surface within a total slab height of about 2 m. The experimental observations resemble the MeteoBlue data apart from the expected snow compaction and transformation of the following days and confirm the presence of a weakest interface.[5]

In the presence of a new snow fall $\Delta H'$ with a density ρ' different from the mean value ρ of the slab over the weakest interface, with a different value H'_C with respect to H_C and with a different acceleration A' with respect to A—posing $A_I = bA_{II}$, $A_{II} = A$, where b is a constant—we expect a new value of $\Delta H' = \Delta H \times \rho/\rho' \times A'/A \times H'_C/H_C$ (and proportional Δt, up to saturation here at 135 min). For example, considering E5 as treated in Puzrin et al.,[4] for H'_C = 2.14 m, i.e., following Chiaia et al.,[5] the avalanche would have been expected 17.8 min later instead of the 13.2 min previously deduced, 35.6 min later if we assume in addition ρ/ρ' = 2 (new snow with halved density), or 71.2 min later if we further assume in addition A'/A = 2 (doubled ground acceleration).

In conclusion, 5 years after that dramatic Wednesday, if we stick to the facts, (1) there is no evidence of earthquake triggering for the Rigopiano avalanche, (2) the earthquake triggering is very unlikely, (3) even if it cannot be proven nor disproven, (4) these earthquakes are equivalent to only a few centimeters of snow precipitation, and (5) even assuming earthquake triggering, the avalanche would have likely occurred the very same day even in absence of earthquakes.

Such natural disasters are inevitable and will unfortunately continue to happen in the future. By exploiting our knowledge of mechanics and materials, we could potentially predict their occurrence more accurately, develop appropriate response measures, and thereby minimize future societal and economic damage, destruction, and especially tragic loss of human lives.

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DECLARATION OF INTERESTS

The author declares no competing interests.

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