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Interactive comment on "Single-block rockfall dynamics inferred from seismic signal analysis" *by* Clément Hibert et al.

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(Please read the supplementary PDF version of the review because the format of the online version is not good.)

The purpose of this paper is to investigate the link between the dynamics of a single block falling down a slope and the characteristics of the seismic signal radiated during the impacts of this block on the ground. The authors conducted a release of 28 blocks of masses m ranging from 76 kg to 472 kg on a steep slope constituted of unconsolidated soft-rock. Using a couple of cameras, they were able to retrieve the trajectories of the blocks and compute their speed of impact Vz, for each impact. In addition, the authors installed a network of 5 seismic stations, with sampling frequency 100 Hz for one station and 1000 Hz for the others, in order to record the seismic signals emitted

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Discussion paper

by the impacts of the blocks on the slope.

For a selection of rock falls for which the signal-to-noise ratio is high and for which the block did not roll and stop on the slope, the authors then computed the absolute seismic amplitude at the position of the impact and the absolute radiated seismic energy for each impact. The estimation of the absolute seismic amplitude and radiated energy required the authors to evaluate the attenuation of seismic amplitude with distance from the source and as a function of frequency.

For each of the selected impacts, the authors then compare (1) the absolute seismic amplitude with the momentum p = mVz of the block before the impact and (2) the radiated seismic energy Es with (i) the kinetic energy Ek of the block before the impact, (ii) the potential energy Ep lost by the block during the impact and (iii) a function of the mass m and speed of impact Vz of the block derived analytically from Hertz model of elastic impact by Farin et al. (2015): m Vzˆ(13/5). They also compare the radiated seismic energy Es with the parameter mVzˆ(0.5), that was observed to better fit the data for similar experiments of blocks impacts conducted by Farin et al. (2015). The authors chose to relate the seismic parameter X to the dynamic parameter Y using a linear relationship X = aY + b. The coefficient of regression Rˆ2 varies from 0.31 to 0.64 with the best fits observed between the absolute seismic amplitude and the momentum mVz and between the radiated seismic energy Es and the kinetic energy Ek of the block. Finally, they invert these empirical scaling laws in order to express the mass m and the speed Vz of the blocks as functions of the seismic amplitude and the radiated seismic energy Es. They use this scaling laws to retrieve the masses and speeds of the blocks that they compare with the real values. A relatively good correlation is observed, within $\pm$ 50% of the real value.

The authors conclude that their study show that there is a good correlation between the seismic amplitude and the momentum of the block before impact and that this may help to get information on granular flows dynamics from the generated seismic signal.

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Discussion paper

The paper is globally clear to read and the successive sections follow naturally each others. I find personally that it is interesting to have new data of seismic signals generated by block impacts and be able to evaluate the dynamics of the block in parallel in order to better understand the link between the two on the field. The authors took care to evaluate the dynamics of the block with a good precision, with an uncertainty less than 1 m sˆ-1 for block speeds varying from 6 m sˆ-1 to 17 m sˆ-1. When we compare seismic parameters to dynamic parameters, it is important to evaluate the absolute seismic parameters at the source because they strongly depend on the distance between the source and the instrument and on the frequency. Care has also been taken in evaluating absolute seismic parameters in this paper. Therefore I think the presented data are of good quality. However, I think that the paper needs a major revision before being considered for publication because it contains major confusions and misinterpretations of the data.

My main concern in is the fact that the authors say several times in the paper that they show a scaling (or proportionality) between the seismic amplitude and the momentum of the block while they are showing a linear relationship. There is a important confusion here because a scaling (or proportionality) is a relation Y = a X while a linear relationship (as showed in this paper) is Y = aX+b, with b a nonzero constant. This has a different implication for the interpretation of the data. The paper should be rewritten with this point in mind. This confusion is particularly problematic when the authors are comparing the parameter mVzˆ(13/5) derived by Farin et al. (2015) to the radiated seismic energy Es. They are testing a law Es = a mVzˆ(13/5) + b and claim that the fit of this law with their data is better than it was in the paper of Farin et al. (2015). However, the analytical scaling law established in Farin et al. (2015) and tested with their rockfall experiments was Es = a mVzˆ(13/5) (with b=0): this is a different law. In the present paper, the parameter b is not 0 and it is several orders of magnitude larger than the parameter a. The fit Es = a mVzˆ(13/5) (with b=0) should be tested instead. Moreover, since the parameter b does not exist in the analytical model, I do not know if this parameter has a physical meaning, even though it has the dimension of an energy.

Also, an analytical expression of the proportionality coefficient a is given in Farin et al. (2015). The exact law and empirical law (with the exact and empirical value of a) could be compared to the seismic energy Es. An interesting question when we study the seismic signal generated by rockfall is to establish their energy budget, i.e. determine the amount of kinetic energy or potential energy lost that is radiated in the form of elastic waves. In other words, I think the authors should compute the value of the ratios Es/Ek and Es/Ep (or maybe also Es/(Ek+Ep)). These ratios should be less than 1 and the rest of the kinetic and/or potential energy lost is dissipated in plastic deformation (irreversible deformation) of the ground or in viscoelastic processes (heat). These ratios can then be compared with that computed for larger rockfalls in the crater of the Piton de la Fournaise, La Reunion Island (Hibert et al. 2012) or with that obtained in other studies (e.g. Deparis et al. 2008). Thus we could see if the energy budget for one single impactor is different than for a rockfall constituted of several blocks. These ratios are proportionality relations between seismic and dynamic parameters. In a nutshell, I think that proportionality relationships Y=aX between seismic and dynamic parameters would have much more interesting implications for interpretations of the seismic signals generated by rockfalls than linear relationships Y=aX+b. Besides, no confusion should be made between the two kinds of relationship. A linear relationship may better fit the data of this paper than a proportionality law X = a Y but in this case, both fits (X = aY+b and X = aY) should be shown and a physical interpretation of parameter b should be given.

An other problem I see is when the authors want to retrieve the mass and the speed of the blocks from the seismic signal. Two seismic variables are used: the absolute seismic amplitude and the radiated seismic energy. However, I do not think these two variables are independent of each others. I would not be surprised if the radiated seismic energy is proportional to the squared absolute amplitude. In this case, the mass and the speed could be expressed as functions of the radiated seismic energy alone. The problem is that I don't think it is possible to retrieve two independent dynamic parameters from only one seismic variable. An advantage of the present study compared with the previous ones (e.g. Farin et al. (2015)) is that the authors have access to higher frequencies up to 500 Hz, with respect to 50 Hz before. Therefore, they potentially have access to all the frequencies emitted during the impacts, contrary to the previous study. Thus an interesting seismic parameter to evaluate would be the mean frequency of the seismic signal. the analytical model of impact of Hertz shows that the mean frequency is inversely proportional to the mass m of the block. It would be interesting to test this scaling. The mean frequency of the signal is independent of the radiated seismic energy so if empirical scaling laws are established between these two parameters and the mass and the speed of the block, the laws can be inverted to retrieve the masses and the speeds. Farin et al. (2015) established two analytical scaling laws relating the mass and the speed of the block to the radiated seismic energy and the mean frequency of the signal, i.e. equations (29) and (30) of their paper. I would be curious to see if these equations can provide reasonable values of the masses m and the speeds Vz of the blocks with the present experiments. Maybe the absolute seismic amplitude and the radiated seismic energy are independent of each others. In that case it should be shown somewhere. Besides, if the mean frequency of the signal is not inversely proportional to the mass of the block, it would be interesting to show it. That would mean that Hertz's model does not apply on the field.

My following comments refer to specific lines in the paper.

The abstract needs a context sentence.

page 1 line 8, line 10. . ., 'Âăthe energy of the corresponding part of the seismic signalÂă' , 'the energy of the seismic radiationÂă',. . .Âătry to always call this energy is the same way all along the paper, for example 'Âăthe radiated seismic energyÂă' because it is sometimes difficult to understand to what energy you are referring to.

Âăpage 1 line 8: 'ÂăOur results suggest that the amplitude of the seismic signal scales with the momentum of the block at the impact.Âă'. No, be careful thorough in the paper: a scaling is a proportionality, not a linear relationship. This is important.

page 1, line 12: ’Âăthe masses and the velocitiesÂă’ or ’Âăthe mass and the velocityÂă’

page 2, line 19: precise that this is true in the frequency range 3 Hz to 10 Hz

page 2, line 20: ’The authors also demonstrated that the maximum amplitude of the seismic signal, corrected from propagation effects, scales with the bulk momentumÂă’: That was also a linear relationship, not a scaling (i.e. proportionality).

page 2, lines 27-32: this paragraph needs rewriting: line 30: ’ÂăThe impulse imparted to the solid Earth by a bouncing particle within a granular flow will be proportional to the kinematics of the particle, and the amplitude of the seismic wave will be proportional to the magnitude of the impulseÂă’. This sentence is not very clear, it particular ’proportional to the kinematics of the particleÂă’ does not mean anythingÂă : I would rather say that the seismic amplitude is proportional to the impulse, which is itself proportional to the speed of the particle (in theory). Line 31: ’ÂăHowever, this assumption raises an important issue: what is the link between the dynamics of a single bouncing particle (a rock for example) and the seismic signal it generates?Âă’. Be more specific because you said just before that the seismic amplitude is proportional to the impulse.

page 2, l. 34: not exactly true: the mass and the speed of an impactor can be related to the radiated elastic energy and the mean frequency of the signal. Do not write ’Âăat a given frequencyÂă’, it could be misinterpreted.

page 3, l.1: precise here what is the relation you are referring to: Es = a mvˆ(13/5).

page 3, l.4: It is very strange for me why you say that having frequency < 50 Hz is a limitation (which is true) but then you are filtering your signals below 50 Hz in the following (p 6, l 30). Why don’t you take advantage of having frequencies higher than 50 Hz in order to improve the estimate of the masses and speeds of the blocks with respect to the previous study? Moreover, you know the mass and the speed of the blocks so you can evaluate a theoretical mean frequency of the signal generated by an impact using Hertz theory of impact and then compare with the measured mean frequency in your data. You would know if your seismic stations are sensitive to the whole frequency spectrum emitted during the impact or if you are loosing energy in the highest frequency (if the measured mean frequency is smaller than the theoretical mean frequency). This would help you to interpret the difference between the measured radiated seismic energy Es and the parameter a mVˆ(13/5): normally the measured Es should be smaller than a mVˆ(13/5) at high frequency if you are not sensitive to the highest frequencies. Finally, if you don't obtain any satisfying results using the mean frequency, it would mean that the mean frequency is not a reliable enough parameter to use to extract information from the seismic signal generated by impacts on the field: this is an interesting result.

page 3, l. 4, you should rather say 'Âăa great part of the energy liberated at the impact is at high frequencies (> 50 Hz)Âă. . .'. An other important limitation we had was that there was no synchronization between the seismic signal and the movies. . .

page 3, l.6-11: You should better highlight what is new in your study with respect to the previous study: you use several seismic stations that can record higher frequencies, up to 500 Hz and a better identification of the seismic signals associated with each impact of the blocks.

page 3, l.25: Is the torrent producing a lot of seismic noise?

page 4, l.6: Define clearly what are the potential energy lost and the kinetic energy as a function of the mass and the speed of the block, and show these relations on the axis of Figure 4. Also: is the speed of impact Vz vertical or inclined with respect to the slope/vertical? Can you observe an effect of the angle of impact with respect to the normal to the slope on the radiated seismic energy? Are more inclined impacts less seismically efficient (lower Es/Ep) than more normal impacts? This might potentially explain part of the discrepancy.

page 4, l. 11: Write here the range of values the speed of impacts Vz can take because we don't know if 1 m sˆ-1 is a large and small uncertainty.

Figure 1c: not clear what the colored points are referring to. The text is the figure is too small, especially along the torrent.

page 5, l. 4, the Figure 2b also shows the attenuation of small frequencies. Rephrase the sentence.

page 5: It is not clear how you obtain the equation (2) and what the index ij are representing for B. You should directly say that B depends on frequency and show B as a function of the frequency, on a Figure for example (maybe in Appendix), so that we can know what is the quality factor Q. If you assume that B does not vary with frequency then give the value of B (or a range of values).

page 5, l. 23: Can you measure the wave speed in this specific site with your present seismic data by measuring the difference of time travel after an impact between several seismic stations?

page 6, l. 30: What a pity not to use the high frequencies > 50 Hz. There may a lot of interesting information in it.

Figure 4: Do you observe a correlation between radiated seismic energy Es and the squared momentum |p|ˆ2 ? See my first comment about the law X = a Y and the energy ratios. (d) Why is alpha negative ? The lost potential energy is not negative so it should not. See my first comment: the laws established and tested in Farin et al. (2015) are Es = a mVzˆ(13/5) and Es = a mVzˆ(0.5), not the ones you are showing. The caption of the figure can be simplified: 'ÂăDecimal logarithm of the seismic energy Es of the seismic signal generated at the impact as a function of (b) Ek, (c) Mass, (d) Ep, (e) mVzˆ(0.5) and (f) mVzˆ(13/5).Âă'

page 9, l. 3-9: Rewrite this paragraph in accordance with my first comment.

page 9, eq. (6): I am not sure that the absolute amplitude and the radiated elastic energy are independent variables. Also write explicitly the equation for the speed Vi as a function of the signal parameters.

Table 1, Fig 5: Represent the results of the inversion more uniformly: a figure with two plots showing (a) mi as a function of mr and (b) Vi as a function of Vr, with error bars and the line Y=X would be much clearer than a table and a histogram that mean to represent the same thing for m and Vz.

page 11, l.4: 'Âălinear scalingÂă' => linear relationships.

page 11, l. 7: 'Âăthe seismic radiation released at each impact scales linearly with the potential energy lostÂă': no.

page 11, paragraph 2: You did not verify this scaling law either. 'ÂăIn our study the instruments we deployed permitted to record most of the energy generated at impacts. This underlines the importance of choosing adequate seismometers, capable of recording the whole seismic energy generated at the impacts,Âă for future studies.Âă'Âă': Yes but you did not take advantage of this because you filtered the signals below 50 Hz while energy is clearly visible at more than 200 Hz on Figure 2a. . . Therefore you can not use this sentence to explain why you observed better correlations.

- page 11, last line: 'ÂăWe show that the maximum amplitude of the seismic signal generated by the impact of a single particle is proportional to its momentum.Âă' This is false.

- page 12, first line: 'The source of the seismic signal generated at this given time might therefore be the sum of the impulses imparted by the particles to the ground.Âă' I do not think we can say that because the signals emitted by two particles impacting the ground at roughly the same position and time can destruct or add themselves, depending of their phase. The energies of each impacts may be added, however (see the paper of Tsai et al. 2012 on the seismic noise of river: 'ÂăA physical model for seismic noise generation from sediment transport in riversÂă', GRL (2012).). Moreover, in the granular flow experiments we did with Anne Mangeney during my PhD (cf. Farin, M. (2015),ÂăÉtude expérimentale de la dynamique et de l'émission sismique des instabilités gravitaires. IPGP, France.), we showed that the scaling law that relate the radiated seismic energy to the mass for a single impactor is not the same as for a granular flow of multiple particles of the same size. The relationship between the radiated seismic energy and the mass and the speed of the particles in a granular flows is much more complex than for one impact because all the particles are interacting with each others and each of them move in a random direction with respect to its neighbors (in an agitated flow) and each of them has a different fluctuating speed (instantaneous speed - mean speed of the flow). Therefore, the seismic amplitude generated by a granular flow does not simply scale (nor has a linear relationship) with the momentum of one particle in the flow. As you say in the last sentence, numerical models (DEM or statistical models like kinetic theories of granular gas) can help us better understand the complex link between particle/flow dynamics and seismic signal in granular flows.

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Please also note the supplement to this comment:
http://www.earth-surf-dynam-discuss.net/esurf-2016-64/esurf-2016-64-RC1-supplement.pdf

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