Evaluating earthquake-induced rockfall hazard by investigating past rockfall events: the case of Qiryat-Shemona adjacent to the Dead Sea Transform, northern Israel

Authors' Comments for Reviewer #1

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General: Reviewer #1's comments were of great contribution to the manuscript, addressing these issues and revising the text and figures accordingly has benefitted the manuscript and helped to obtain better supported arguments for our discussion and conclusions, and improve the way we present our results and the discussion. We thank the reviewer very much for taking the time to raise questions and make suggestions that improved the manuscript significantly.

All of the reviewer's comments were addressed or answered and changed in the manuscript. Our reply comments are brought here in a numbered item-list detailing each of the comments with the explanations and actions we introduced accordingly.

(1) **Comments from Referee:** Section 3.1. Authors should provide some information about the block size; this should explain why in the subsequent sections they use only selected values of the block sizes.

Author's response: This was missing here although detailed later in the text of the results. Details of the field mapped block sizes were added to section 3.1 and its paragraph was revised. The use of selected block values for the simulation was added to the next section (3.2) to be presented before the calibration methodology.

Author's changes in manuscript: section 3.1 revised and added the following: "76 blocks were mapped and measured in the field with volumes varying between 1.0 m^3-125.0 m^3."

Section 3.2 was added the following: "The simulated block volumes were binned into size scales of 1, 10, 50, 100, 125 m^3, with corresponding block diameters of 1.3, 2.7, 4.6, 5.8 and 6.2 m, respectively (assuming spherical block geometry)."

(2) **Comments from Referee:** Section 3.3. The calibration method is not clear, since two out four pink lines are out of the field mapping (green polygon in Fig. 3) and it seems that only one of the lines intersects a relatively boulder-dense area. Please, explain better this point and give the number of the field-mapped rock-blocks ("high" is too generic).

Author's response: The text was revised accordingly to better explain the calibration profiles locations.

Author's changes in manuscript: This paragraph in section 3.3 now reads as follows:

"CRSP calibration using back-analysis was performed along four slopes (pink lines in Fig. 3) located at the N and S parts of the prominent Ein-El-Assad source outcrop, where a relatively high number of field mapped (50 blocks out of 76) and aerial photo mapped rock-blocks (65 blocks out of 200) were observed: two profiles 100 m apart from each other in the N part with observed field mapped and areal-photo mapped blocks; two profiles 100 m apart from each other in the S part with aerial photo mapped blocks".

(3) **Comments from Referee:** Line 31, page 4, a different letter for the velocity (e.g. u) should be used, since V is the block volume.

Author's response: This is a good point. All 'Vx'mentioned in the section were replaced to 'Ux'

Author's changes in manuscript: All 'Vx'mentioned in the section were replaced to 'Ux'.

(4) **Comments from Referee:** A simulation is supposed to output a mean value and an uncertainty, but the reported results of the sensitivity analysis are sharp numbers. Could the authors give an uncertainty on these numbers?

Author's response: The optimal Rn=0.22 value was extracted using a regression curve from the Δ*MD* values resulting from testing end members 0.12, 0.2, 0.25. when fitted a regression with minimum difference between simulated and observed maximum travel distances the regression yielded a minimum of 0 difference at 0.22. an explanation for this and an estimation for the change in travel distance per 0.01 change in Rn was revised in the text.

Author's changes in manuscript: the text in section 3.3 was revised accordingly and now reads as follows:

"An exponential regression curve was fitted for the above R_n values (0.12, 0.2, 0.25) vs their corresponding Δ*MD* values (-90, -30, +160 m), which yielded Δ*MD* = 0 m (minimum difference between observed and simulated maximum travel distance) at R_n = 0.22. Thus, calibration was determined optimal for R_n = 0.22. We estimate that 0.01 change in Rn will yield 15-30m change in maximum travel distance. Calibration profiles are 450-750 m, yielding 2%-3% variability for 0.01 change in R_n."

(5) **Comments from Referee:** Is the surface roughness S a dimensionless quantity in the CRSP algorithm? If not, please add the proper measurement unit (feet, meters?.

Author's response: Surface roughness was measured in the field according to the CRSP program manual. It is given in meters but varies according to the radius of the simulated block. Hence an S value per simulated block diameter needs to be measured in the field and used in the software. S values were revised to have meter units in the text.

Author's changes in manuscript: text revised accordingly as follows:

"… using the above detailed best-fit values R_n =0.22; R_t =0.70 and the field-measured surface roughness S values S=0.1, 0.3, 0.4 m for block diameters D=1.3, 2.7, 4.6 m respectively, and S=0.5 m for D=5.8 and 6.2 m (all S values were measured in the field per block diameter according to CRSP software manual)."

(6) **Comments from Referee:** Lines 6 to 8, page 5. This statement is not clear, please rephrase it.

Author's response: paragraph was modified to better explain and detail the calibration process.

Author's changes in manuscript: lines 6-8 were revised accordingly and now read:

"R_t value was determined to 0.70 following our initial calibration value, which is also recommended by Jones et al (2000) for firm soil slopes. To validate these coefficients, further simulation runs along the four calibration profiles were performed for all block sizes (D=1.3–6.2 m), using the above detailed best-fit values R_n =0.22; R_t =0.70 and the field-measured roughness S values: S=0.1, 0.3, 0.4 for block diameters D=1.3, 2.7, 4.6 m respectively, and 0.5 for D=5.8 and 6.2 m (all S values were measured in the field per block diameter). All slope cells were given the same values to maintain model simplicity. The travel distances of simulation results were compared with the observed travel distances (from field mapping and aerial photo mapping). The fit between observation and simulation is plotted in Fig. 5."

(7) + (8) **Comments from Referee:** Section 4.1. The scaling exponent of the probability density function is -1.17. How much are the authors confident on the second decimal number? Could you give an estimation of the uncertainty on this number? If not, I would give -1.2 as a likely value.

Lines 23 to 28, page 6, need to be better explained. How does Eq. (2) relate to Eq. (3)? In Eq. (2), the cumulative probability for blocks with diameter less or equal to D is the sum from Vmin to VD (the integral for very small bins) of the probabilities calculated for each bin. Applying the relationship between volume V and diameter D for a sphere (V = 4/3Â°upiÂ°u(Dˆ3)/8) in Eq. (2) does not yield the expression shown in Eq. (3). Could you explain the difference? As in the previous comment, how much are the authors confident on the decimal values in Eq. (3)?.

Author's response: The reviewer suggestion to round the power law to -1.2 is correct. The -1.17 It is yielded from the regression but the R2 is not very high (0.72). The text was revised to detail the calculated -1.17 power and suggest to round it to -1.2. The discrepancy between Eq 2 (all blocks 1-125 m^3) and Eq. 3 (only block diameters 2.7-6.2 for volumes 10-125 m^3) is because eq 3 is used for correlating our actual volumes (diameters) of the simulated larger size blocks in which we are interested for the hazard estimation. The smaller scale blocks (1 m^3) are of less interest for hazard estimation as we focus on the larger blocks as potential worse-case hazard in our simulations. We later use eq 3 for prediction of probability for occurrence of blocks at sizes up to 10-125 m^3 (D=2.7-6.2 m) for hazard calculations.

Author's changes in manuscript: The text in section 4.1 regrading these two comments was revised accordingly and now reads as follows:

"Our results show that the volume of the individual rock blocks from the studied area exhibits a distinct negative power law behavior, with a scaling exponent of the right tail of α = -1.17 (R^2 = 0.72; Fig. 6). This conforms to what was found by others who examined natural rockfalls with observed α ranging: -1.07 - -1.4, e.g., Guzzetti et al. (2003) Malamud et al. (2004) Brunetti et al. (2009). The scaling exponent is also similar to the value α = -1.13 obtained experimentally by Katz and Aharonov (2006), while Katz et al. (2011) found a larger scaling exponent, α = -1.8. Since our data yield a moderate R^2=0.72 we round the power to -1.2 (instead of -1.17). In accordance, the probability density function (PDF) for rockfall volume (*p)* may be presented as a power law of the form (Dussauge-Peisser et al., 2002; Dussauge et al., 2003; Guzzetti et al., 2003; Malamud et al., 2004) Eq. (2):

$$p = 0.4V^{-1.2} \quad (2)$$

where *V* is the given block volume in m^3. The power law is -1.2 and R^2 = 0.72 (for the 76 field mapped blocks plotted in Fig. 3). This power law can be used for comparison to other rockfall studies elsewhere..

To simplify the hazard evaluation and relate to the more prominent hazard which larger block sizes impose (thus removing the 1 m^3 smaller blocks from the simulation runs) the block volumes were binned into size scales of 10, 50, 100, 125 m^3, with corresponding block diameters of 2.7, 4.6, 5.8 and 6.2 m respectively (assuming spherical block geometry). Cumulative frequencies were used to derive cumulative probabilities for each block size (Table 1). The probability values per block diameter (Table 1) were fitted a regression curve in Excel (R^2 = 0.97), yielding the probability (p_D) for a block of given diameter (*D*) or smaller following Eq. (3):

$$pD = 0.412Ln(D) + 0.262 \quad (3)$$

The probability calculated from Eq. 3 per block diameter differs than the probability in Eq. 2 per its matching block volume because of the different use of the two equations: Eq. 2 power-law details our full field-observed data of block sizes and can be used to characterize the dataset and compare it to other block catalogs in other studies, while Eq. 3 yields an empirical prediction for probability of occurrence for the larger block diameters (D>=2.7 m; V>=10 m^3), which were actually used later in the CRSP simulations for hazard analysis."

(9) **Comments from Referee:** Section 4.2.1. Could authors give a definition of the profile cell? What is the size of it? Fig. 7 is potentially interesting, but I'm not sure to have fully understood it. The number of profiles shown on the horizontal axis is 30, while in the Figure caption is 25. The vertical axis title should be better placed along the graduated curved axis. Grey circles are defined as "other cells". Could the author explain better what these other cells represent?

Author's response: An explanation for slope cell in CRSP was added in section 3.2 in the methods. Figure 7 has been modified (profile axis numbers fixed) and now includes also an illustration of the CRSP model slope cells, x% stop angles and the stop swath. Additional explanation of the figure was added to the figure caption and is referred to in the text in section 4.2.1

Author's changes in manuscript:

* Methods section '3.2 rockfall simulations' was added the following explanation about the slope cell: "The slope surface in CRSP is divided into slope cells, which boundaries are defined where the slope angle changes, or where the slope roughness changes (Jones et al., 2000)."

* Section 4.2.1 was added the following reference to figure 7: "Further details and illustration for slope cells and stop angles are given in Fig 7."

* Figure 7 revised caption now reads as follows:

"(a) Illustration of the CRSP modelled slope cells and explanation of the terms 'x% slope angle' (e.g. 50% stop angle is the angle of the slope cell where 50% of the blocks stop) and 'stop swath' (the farthest distance along the last cell where 100% of the blocks stop)**. (b)** Slope gradients of slope cells and gradients at stop angles. Tangential axes (X and Y axes) denote simulated profile numbers 1 to 25. Radial axis denotes the slope angles. Gradients for all cells per profile are plotted on an arc between 0 and 90 degrees: Red circles are 100% stop angles (slope angle of the profile cell at which cumulated 100% of simulated blocks stop); blue triangles are 50% stop angles; gray circles are all other cells in the profile. For example: the cells along profile 16 have slope angles that vary between 8°-36°; the 100% stop angle is 11° (red circle) and the 50% stop angle is 8° (blue triangle). The red line represents the mean of all 100% stop angles for all profiles at 7.7° and the thick black lines represent its SD of 2.3°."

(10) **Comments from Referee:** Line 11, page 7, how do you calculate the range of variation 3_-12_ from a mean of 7.7_ and a SD of 2.3_?

Author's response: the variation presented is for the whole range of stop angles. the mean and 1sigma SD (2.3) yield a 6.4-10 deg. Text revised accordingly.

Author's changes in manuscript: revised text now reads as follows:

"100% stop angles for all profiles (red circles in Fig. 7) vary between 3°-12° with a mean of 7.7° and *SD* = 2.3° (1σ=6.4°-10.0°); 50% stop angles (blue triangles) vary between 3.2°-25.8° with a mean of 10° and *SD* = 5.3° (1σ=4.7°-15.3°). All other cell slope angles in all profiles (gray circles) vary widely between 7°-88° with a mean of 29.4° with *SD* = 17° (1σ=12.4°-46.4°)".

(11) **Comments from Referee:** Section 5.1. The sentence: "Thus, rainstorms are ruled out as a favorable triggering mechanism" should be smoothed since it is supported by a very poor statistics, i.e. only two seasons.

Author's response: the statistical data was re-phrased, and more importantly – a comparison of another rockfall study in Yosemite in which 27% (>100) of reported rockfall events in 150 years were triggered by rainstorms is brought as a counter example to support our suggestion that rainstorms are not a favorable trigger, with no reports of rockfalls for the past 74 years at all, in spite of heavy rainstorms in the study area were reported.

Author's changes in manuscript: The text was revised and now reads as follows:.

"The correlation of rockfall events to historical extreme rainstorm events is limited due to the lack of long enough historical rainstorm record. However, in the entire documented climatic history of the area (measurements conducted in Kfar-Blum station, 5 km away from the study area, since 1944; IMS, 2007) and even following the extremely rainy winters of 1968/69 and 1991/92, in which annual precipitation in northern Israel was double than the mean annual precipitation (IMS, 2007), until 2018 - no significant rock-mass movements and rockfalls are reported in the study area. Wieczorek and Jäger (1996) reported that out of 395 rockfall events in the Yosemite Valley between 1851-1992, the most dominant recognized trigger for slope movement (27% of reported cases) was precipitation during the colder and wetter part of the season and point out the influence of climatic triggering of rockfall. In our study area – during half that period (74 years of measurements) – not a single event of rockfall was reported, versus ca >100 cases (27% of 395) reported in Yosemite. Based on this large difference we suggest that rainstorms might be ruled-out as a favorable triggering mechanism in our study area".

(12) **Comments from Referee:** In Sect. 5.2 the correlation observed between rockfall events and earthquakes is investigated only for the largest blocks, therefore rainstorms cannot be ruled out for small-size blocks.
Author's response: That is true. The prerequisite for OSL dating was using large blocks, hence any correlation to earthquakes is for the larger blocks (V>= 8 m^3 / D>=2.5 m). However – the rockfall simulation blocks used for hazard analysis also answer to these volumes (smallest simulated blocks were 10 m^3 or D=2.7 m). Additionally, since the larger blocks pose greater hazards in terms of destructive potential, we aimed for analysis of the larger blocks for relevance to the rockfall hazard estimation. The previous section 5.1 was revised according to reviewer's notes and now discusses the rainstorms as possible trigger (and suggests they are not a favorable one).

Author's changes in manuscript: At the beginning of section 5.2 the following was added: "The following discussion relates to blocks of sizes equal or larger than 8 m^3 (D>2.5 m) as the OSL dated blocks were of sizes 8-80 m^3. These volumes fit the CRSP simulation analyses of all blocks in the study, as the smallest simulated block for the hazard estimation was 10 m^3 (D=2.7 m)."

(13) **Comments from Referee:** Section 5.3.2. This subsection, which is the main outcome of the manuscript requires to be rewritten in a more understandable form. The hazard contains usually three terms: one is a time-dependent term, one is size dependent and another one is the susceptibility. Starting from this definition the author should describe each term on the base of the results described in the previous sections of the manuscript.
Author's response: Thank you for this remark. The text in section 5.3.2 was completely revised following the reviewer's recommendation.

Author's changes in manuscript: section 5.3.2 now reads as follows:

"We discuss the hazard probability by addressing three terms: time dependency, size dependency and susceptibility.

Time dependency: we derive the recurrence time for rockfalls in the study area from our OSL dating results ,which correlate to past earthquakes as detailed above. Thus, we can calculate the probability of a rockfall occurrence P_{EQ} in the next 50 years, assuming earthquake magnitude M=6 as the threshold for rockfall: P_{EQ} = 50/550 = ~0.09 or 9%. We do not present a time-dependent earthquake recurrence interval calculation because the time passed since the last large earthquake is not well constrained.

Size dependency: we relate to potential rockfall block sizes following our discussion of block sizes observed in the field and binned by sizes (D=2.7, 4.6, 5.8, 6.2 m) which correspond both to the OSL dated blocks and the CRSP simulations. The probability for each of these block sizes or smaller is predicted by Eq. (3). Considering the time dependent probability and the probabilities for given block sizes detailed above, the probability for rockfall hazard per specific block size (H_R) may be predicted as Eq. (5):

$$H_R = (1 - P_D) \cdot P_{EQ} \qquad (5)$$

where P_D is the cumulative probability per block diameter D (Table 1) and P_{EQ} is the rockfall occurrence probability calculated above to be 9%. Accordingly, predicted H_R for the next 50 years for block diameters D between 2.7 - 6.2 m is H_R ~3% and for larger blocks only, D between 4.6 - 6.2 m (V>50-125 m^3) is H_R ~1%.

Susceptibility: The urban inhabited area subjected to rockfall hazard for travel distances of the large blocks (D = 4.6-6.2 m, V >50-125 m^3 is about 50,000 m^2 (0.05 km^2) as mapped in Figs. 8-9 and discussed above. The area considered under direct rockfall impact hazard totals to 1.55 km^2 (Fig. 8) and includes the slope above town premises and the urbanized area. We conclude that this area has a probability H_R of ~1%-3% for impact by rockfall in the next 50 years."

(14) **Comments from Referee:** Technical corrections See attached PDF file.

Author's response: **All reviewer's technical corrections were implemented in the text accordingly** (including grammar, revision of paragraphs for details, clarifications or better English).

Author's changes in manuscript: **We implemented many technical changes throughout the text and figures following all reviewer's comments**.

Only in one place the suggested technical correction/notes were not implemented, for which explanation is given here as follows: Page 30 – reviewer comment: The figure could be more readable if the triangles and the numbers were only on the yellow line.

Author's response: The triangles and numbers appear both on the yellow line and the red dashed line in ptofiles 8-9-10-11-12-13-14-16 because these are the profiles where block impact is predicted to hit town border. The yellow line is the predicted stop line and the red dashed line is where the blocks are predicted to hit town premises before stopping. For each of these profiles there is double nomenclature: (1) at impact point where kinetic analysis is performed: a triangle marking the location of impact and a 'sword'profile number; (2) at predicted stop point: a triangle marking stop location and a regular profile number.

Author's changes in manuscript: No changes made to Fig. 9 in page 30.

Revised figures 4 and 7 appear in the next pages

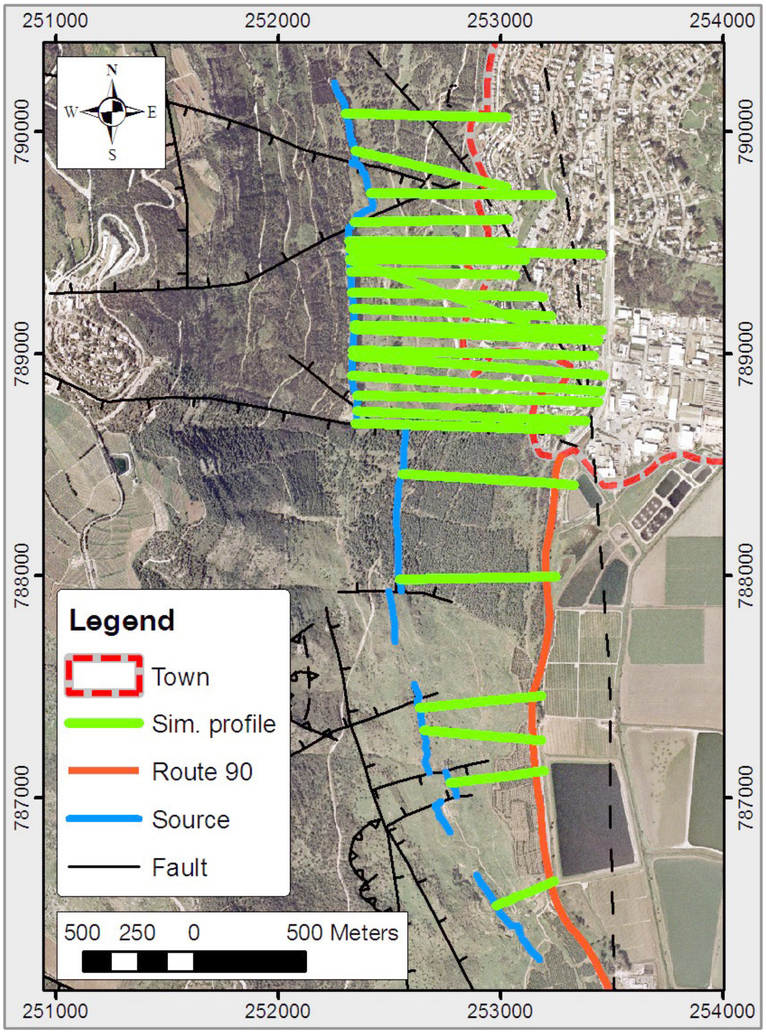

Fig.4 – revision included brightening the background for better clarity of the faults (marked in black lines).

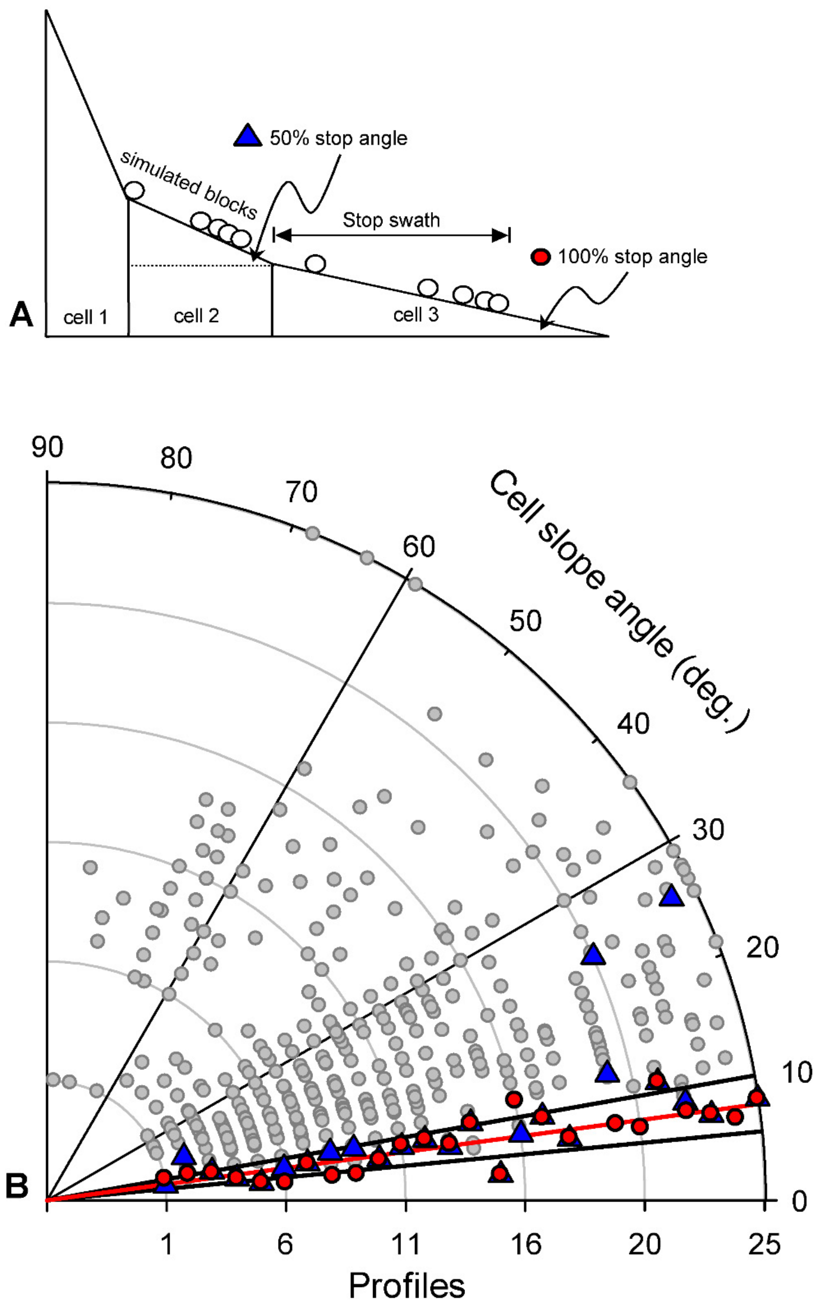

Fig 7. Revised for better clarity of the axes and their representation, and added a top panel which gives an illustration of the terms used in the simulation discussion (profile cells, stop angles, stop swath etc.)