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 #2

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General: The comments and suggestions made by Reviewer #2 have a significant and important contribution to the manuscript quality. The revisions introduced to the text following the review improved the manuscript and helped to consolidate its structure and make it more clear for reading. The reviewer's notes helped to improve the abstract and introduction parts, thus aiding to present the essence of the study, as well as its importance and its relevance to other studies.

* All of the reviewer's comments were addressed or answered and changed in the manuscript.

* Our reply comments are brought in the SUPPLEMENT PDF file in a numbered item list detailing each of the comments with the explanations and revisions-actions we introduced to the manuscript accordingly.

We thank the reviewer very much for taking the time to raise questions and make suggestions that improved the manuscript significantly.

(1) **Comments from Referee:** Abstract - I suggest rewriting the abstract because it is mixed up. It lacks a framework. Aims and methods are not clearly defined.

Author's response: The abstract was revised according to the reviewer suggestions. it is now more complete and details the framework to detail the study.

Author's changes in manuscript: abstract was revised and reads as follows:

"We address a type of rockfall hazard evaluation where the study area resides below a cliff in an apriori exposure to rockfall hazard, but no historical documentation of rockfalls is available. Hence, the rockfall hazard factors like recurrence interval and its possible triggers such as earthquakes or extreme meteorological conditions are unknown. Study case is evaluation of rockfall hazard for the town of Qiryat-Shemona, northern Israel, situated alongside the Dead Sea Transform, at the foot of the Ramim escarpment. Boulders of 1 m^3 to 125 m^3 are scattered on the slope above town, while historical aerial photos reveal that before town establishment, numerous boulders had reached the town premises. We use field-observations to obtain a block-size inventory and OSL dating of past rockfall events, combined with a computer simulation software which was calibrated for the specific site using back-analysis. The simulations were used to predict the rockfall hazard and its spatial coverage. For hazard analysis we mapped the rockfalls, their source and their downslope final stop-sites, and compiled the boulder size distribution. We then simulated the probable future rockfall trajectories using the field observed data to calibrate the simulation software by comparing simulated vs mapped boulders stop-sites along selected slopes, while adjusting model input parameters for best fit. The analysis identified areas of high rockfall hazard at the south-western quarters of the town and also indicates that in the studied slopes, falling blocks would stop after several tens of meters where the slope angle is below 10°. Optically Stimulated Luminescence (OSL) age determination of several past rockfall events in the study area suggests that these rockfalls were triggered by large (M >6) historical earthquakes. Nevertheless, not all large historical earthquakes triggered rockfalls. Simulation results show that downslope reach of the blocks is not significantly affected by the magnitude of seismic acceleration. However, earthquakes appear to play a role as the triggering mechanism of the rockfall. Considering the size distribution of the past rockfalls in the study area and the recurrence time of large earthquakes in the region, we estimate the probability to be affected by a destructive rockfall within a 50 year time-window is of less than 5%. We suggest a comprehensive method to evaluate rockfall hazard where only past rockfall evidence exists in the field. We show the importance of integrating spatial and temporal field-observations to assess the extent of rockfall hazard, the potential block size-distribution, and the rockfall recurrence interval".

(2) **Comments from Referee:** Introduction - It is too brief. I suggest rewriting this section in order to enlarge the scientific literature discussion, for better insert the proposed study in the methodological state of the art.
Moreover, the authors jump from the presentation of the background to presenting their work without any connection.

Author's response: Good point. The first part of the introduction was revised and now has references to previous works dealing with rockfall trigger mechanisms and rockfall dating and hazard estimations.

Author's changes in manuscript: *The first section in the introduction was revised according to reviewer suggestions now reads as follows:

"Rockfalls are a type of fast mass movement process common in mountainous areas worldwide (Dorren, 2003; Flageollet and Weber, 1996; Mackey and Quigley, 2014; Pellicani et al., 2016; Strunden et al., 2015; Whalley, 1984). In this process, a fragment of rock detached from a rockey mass along pre-existing discontinuities (e.g., bedding, fractures) slides, topples or falls along a vertical or nearly vertical cliff. Individual fragments travel downslope by bouncing and flying or by rolling on talus or debris slopes (Crosta and Agliardi, 2004; Cruden and Varnes, 1996; Varnes, 1978; Whalley, 1984, Wei et al., 2014). They travel at speeds of a few to tens of meters per second, and range in volume up to thousands of cubic meters. Due to their high mobility, and despite their sometimes small size, rockfalls are particularly destructive mass movements, and in several areas they represent the primary cause of landslide fatalities (Evans, 1997; Evans and Hungr, 1993; Guzzetti, 2000; Keefer, 2002; Guzzetti et al., 2003; Guzzetti et al., 2005). There are different mechanisms which trigger rockfalls described in the literature: earthquakes (Kobayashi et al., 1990; Vidrih et al., 2001), rainfall and freeze-and-thaw cycles (Wieczorek and Jäger, 1996) are related triggers, and recent studies examined other meteorological factors (e.g. D'amato et al., 2016). In places where no documentation exists for the time of rockfall occurrence - identifying the trigger can help to determine the time of occurrence or the periodic recurrence time of the rockfalls to estimate their potential hazard. However, identifying the triggering mechanism of past rockfalls is not always trivial. Several studies made efforts to date rockfalls of unknown age (e.g. De Biagi et al., 2017; Kanari, 2008; Rinat et al., 2014). Some rockfall sites are overhanging cliffs and slopes under which human settlements or infrastructure are subject to potential rockfall hazard. Such localities require rockfall mitigation measures to protect humans and facilities, for which an estimation of the hazard is required. Here we try to address such a case, where no previous documentation of dated rockfalls exist, yet field observed evidence for past rockfalls is available, but the triggering mechanism and the time of rockfall or recurrence intervals are completely unknown, and an estimation of the rockfall runout trajectories is required."

** The last paragraph of the introduction was added to summarize the methodology that the study suggests for rockfall hazard estimation, and now reads as follows:

"We present a methodology for rockfall hazard estimation based on field-observations to obtain block-size data and dating of past rockfall events, combined with computer simulation software and its calibration to the specific site, which is used to predict the rockfall susceptible area, the impact locations and the kinetic analysis of rockfall impact. These can be used for design of mitigation measures to protect life and property."

(3) Comments from Referee: Methods – I suggest inserting, especially for paragraph 3.1, literature references about the methodology based on the correlation block distribution-dimension

Author's response: References for several of block inventory/dimension and distribuiotm were added to paragraph 3.1. they are also later discussed in the block size distribution results in section 4.1 in the original manuscript.

Author's changes in manuscript: Section 3.1 was revised according to reviewer suggestion and now begins with the following:

"Previous studies dealing with rock block inventories suggested methodologies to test the block size distribution and its relation to rockfall. All of them require some kind of estimation or measurement of the number of blocks and their volumes (Brunetti et al., 2009, Dussauge-Peisser et al., 2002; Dussauge et al., 2003; Guzzetti et al., 2003; Malamud et al., 2004; Katz and Aharonov, 2006; Katz et al., 2011)."

(4) **Comments from Referee:** Results and discussion – These sections are subdivided into too subparagraphs. The readability and understanding of the research outputs could be compromised and made confused by the organization of these sections. I suggest to reorganized these sections.

Author's response: Regarding the **Results**: we have results of many kinds: field mapped blocks, software simulations of several aspects (hazard area mapping, travel distances, kinetic energy calculation, slope angles) and OSL dating of rockfalls. We find it necessary to split the paragraphs in the software simulation results for better presentation of the many types of results we discuss in the study. Therefore we prefer to keep the results in their original order with sub-headings (4.2.1 etc.) for the different analyses we made for the simulation results.

Regarding the **Discussion:** we agree with the reviewer that there is too many sub-headings and they were simplified to single-level headings in the manuscript.

Author's changes in manuscript: Discussion sections were numbered 5.1…5.4 and sub-section headers were removed (e.g. 5.3.1 etc.).

(5) **Comments from Referee:** **Technical corrections** Pag. 1 line 26: better “a rocky mass” than “the bedrock”. Pag. 2 line 23: replace the colon with a dot. Pag. 3 lines 23-24: better “geometry and properties of in-situ rocky mass and of detached blocks”. Pag. 3 line 27: please put the references into parentheses. Pag. 3 line 29: replace the colon with a dot. Pag. 4 line 10: how were the source areas identified?

Author's response: **All of the technical corrections suggested by the reviewer were implemented in the text** (except for one colon that we could not identify in the text in page 3 line 29).

Author's changes in manuscript: Text revised according to reviwer suggestions. Regarding the identification of the source areas – the following clarification was added to the text in the ‘study area’ description:

“Colluvium and rock-mass movement deposits were mapped on the slopes near Qiryat-Shemona (Shtober-Zisu, 2006, Sneh and Weinberger, 2003a), *identifying the blocks on the slope as originating from the Ein-El-Assad formation*.”