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Discussions

Interactive comment on "Assessment of potential seismic hazard for sensitive facilities by applying seismo-tectonic criteria: an example from the Levant region" *by* Matty Sharon et al.

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We would like to thank the unanimous reviewer for his/her in-depth review of the manuscript and his/her constructive and important comments. Following the comments, we have thoroughly revised the article. The manuscript title, introduction, discussion and conclusion chapters were rewritten. We provide below detailed replies to the reviewer's comments and indicate how and where changes were made in the revised manuscript.

1) "the title of the manuscript: "Assessment of potential seismic hazard for sensitive facilities" is misleading and erroneous. The paper does not contain any hazard analy-

sis, or a comparison to existing hazard assessments for the area" Author's response: following the reviewer comment we wrote a new title that reflect this study more accurately.

New title: "Assessment of seismic sources and capable faults through hierarchic tectonic criteria: implications for seismic hazard in the Levant "

2) "There is no discussion on how these results will affect hazard or any direct practical connection between the presented analysis and hazard calculations."

Author's response: We added a section that clarify this important subject to the discussion (See below Sec. 7.1). Indeed, we are not operating hazard statistical calculations. We hope that our new introduction clarify this. The map and the slip rates of Fig. 5, as well as the local seismic intensity that we analysed here, are fundamental inputs for ground shake models and acceleration maps. The Capable faults map, on the other hand, can be used for choosing potential cites for planning special facilities. defining faults parameters, maps and local seismic characters, as we done here, are the first steps in hazard evaluations. We further emphasize that the two maps (Figs. 5, 7) enable defining the relevant faults necessary for regional hazard models, but not necessarily replacing local maps of other faults that required in some standards, when siting in a specific location is considered.

"7.1 Methodological aspects and applications for hazard evaluations Regions with intermediate seismicity rates present a challenge for hazard evaluation; while the hazard might be perceptible, the seismic data and the geological evidences for recent surface rupture are sparse comparing to very active zones. Considering that the earthquake phenomenon is a stochastic process and its predictability is limited, we develop a methodology for mapping and characterizing hazardous faults, by taking advantage of incorporating interdisciplinary information with statistical seismological analyses. Two regional fault maps are presented; one is relevant for regional ground shaking models (Fig. 5), and the other for surface rupture nearby facilities that are particularly vulnerable to this hazard (Fig. 7). In addition to the approach of classifying faults by the recency of faulting or by their recurrence intervals (Machette, 2000 and references therein), we utilize other criteria such as seismological patterns (Sec. 4) and tectonic configuration (Sec. 6.3). In particular, we use the distribution of the earthquake kernel density and the seismic moment kernel density to test the relevancy of faults for different hazards. Fig. A3 reveals that most of the capable faults, which are mapped based on the geological criteria, could have entered the map also by the seismological criterion (ignoring its 6-km fault length limitation). The match between the geological-categorized faults and the area defined by the seismological analysis reinforces the methodological concept of utilizing the two seismological distributions that are, to a large extent, independent of one another. Moreover, faults that are defined here as 'main seismic sources' according to specific tectonic conditions (i.e. slip rate, geometry, structure) are well correlated with the zone defined by our seismological analysis (Fig. 6). This emphasizes the significance of this analysis, especially when slip rates are slow or under debate (as in Sec. 5.2). The internal hierarchic categorization of faults in both maps (Figs. 5, 7) enables separating different fault groups, and can later be implemented if a specific hazard is considered or if risk evaluation is applied. However, we note that although faults are marked by hierarchical criteria, the different categories are in many cases complement each other rather than show hierarchy of the activity level. The grid-based distributions of the obtained seismicity parameters are utilized here together with fault geometry parameters (length and orientation) for defining capable faults. The advantage of this integration is expressed where the seismological criterion (Sec. 6. 3) defines capable faults in regions where young formations are scarce (Fig. 7). Just as important, our database of gridded seismicity, with possible adjustments, can be implemented as an independent source for hazard evaluations, and as a complementary to the regional databases of mapped faults in zones of subsurface faults. Although our methodology is demonstrated for the Israel region, the approach is universal, and is particularly useful in domains of intermediate seismicity rates or limited field evidences. The criteria, when implemented in other re-

gions, should be adjusted according to the regional and local seismo-tectonic settings. For example, our seismicity-based analysis is not considering the orientation and the inclination of the fault surface when epicentre locations and fault traces are correlated together, because most of the faults in Israel region are characterized by steep dips. This cannot be neglected in low angle faults zones or convergence regime. Finally, our approach of hierarchic tectonic criteria for categorizing faults can be applied in principle also when local siting of an infrastructure is considered. However, faults with extremely large recurrence intervals, located along zones that are not covered by young formations might be difficult to detected, even when seismo-tectonic criteria are considered. Moreover, faults that constitute a mechanical potential for slip, such as conjugate fault sets (Eyal and Reches, 1983) or old faults that can be reactivated by stress triggering (Stein et al., 1997) are not defined as capable in our regional analysis, unless further geological or seismological evidence for Quaternary activity exists. Therefore, local siting, in particular of sensitive infrastructure, might require stricter criteria both for surface rupture and ground shaking, depending on the specific requirements."

3) “"surface rupture and ground shaking are intermixed as 'seismic hazard' and the fault mapping is presented as the answer for both. However – ground shaking and surface rupture are two very different types of hazard. They require different considerations in planning, etc. Is it wise to treat both as one? "

Author's response: Following the reviewer comment, we declare in the introduction that we generate a database of faults that is relevant for several seismic hazards. We demonstrate how we categorize faults for two specific different requirements: one that is aimed to be used in ground shaking models, and the other for siting special infrastructures. We however do not evaluate seismic hazard in this paper, as well as site specific requirements. These are beyond the scope of this paper.

4) "What is very much missing is a thorough discussion on the relationship between the two types of analysis (seismicity based criteria and faulting) – how do you suggest combining the two datasets that you have created ?" (1) In places where they overlap

(e.g. DST), should they both be accounted for in the hazard analysis? If not – what should be the interaction ? (2) In places where they do not overlap (e.g. east Sinai), do you ignore the seismicity criterion? Do you add a 'seismogenic zone'? What is your suggestion? (3) What about places in which the kernel density is zero? Do you think there is really a zero probability of an earthquake occurring there, keeping in mind the short time window used for the kernel density? These are all very important hazard decisions, which this paper does not address."

Author's response: The products of the seismologic analysis are applied differently in the two maps (Figs. 5, 7). We design a seismicity-based criterion that is based on the distribution of two parameters: the earthquake kernel density and the seismic moment kernel density. Faults which are located beyond this pattern are not part of the faults of Fig. 5. The seismological character of a zone is considered as part of criterion for the map in Fig. 7. The success of this selection is further reinforced by the match between the geological-categorized faults and the seismicity criterion (Fig. A3). If this comment, and the three options listed by the referee, refer to the aspect of utilizing the 'gridded seismicity', as an independent database for both surface rupture and ground motion hazards, we emphasis that we focused on generating a database of faults and not on utilizing the seismicity as an independent source for hazard estimations. Therefore, we did not discuss this issue. We now clarify this in the introduction. However, we add a section that discuss the applications of our different analyses to seismic hazard evaluation, included possible usages of the 'gridded seismicity' for hazard evaluations (lines 474-480).

5) "Seems to me that your mapping methodology is more appropriate for surface rupture analysis than for shaking (which also takes into account faults that did not rupture the surface, etc.). Please be more accurate in describing your contribution and its expected useage."

Author's response: A discussion focus on our methodology and its efficiency to both different aims is now written in Sec. 7.1 (See above). Subsurface faults were considered

for capable faults if they are continuation of categorised faults or if there is information that they offset Quaternary formations. On the other hand, for the main seismic sources, they are neglected. Indeed when a local siting process is applied (both for rupture surface and for shaking), information on local fault which are not categorised in our regional analysis should be taking into account.

6) " The abstract says: "our analysis allows revealing the tectonic evolution of a given region". Therefore, it is expected that you will show this later in the results. Nowhere in the paper do you "reveal" anything new about the tectonic evolution that wasn't already known. Therefore – please clarify what exactly is new knowledge gained by this paper? This is typically done by comparing to previous studies or discussing the specific contribution presented in this study.

Author's response: We changed this sentence in the abstract. We also added a new section (Sec. 7.2 in our new discussion), A new figure in the appendix (A4), and conclusion (N. 6, See below) focuses on implications for local tectonics and slip dynamics.

7) "Table 1: title of 2nd column should be 'slip rate' rather than 'strike-slip'. Also, seems to me that the first slip rate that is mentioned for the Yammuneh fault is too low. It references Gomez 2007 but I think his numbers are higher. How exactly did you reach 2.8 mm/yr?"

Author's response: Numbers are for lateral slip rates. 2.8 mm/yr in Table 1 was a mistake and deleted.

8) "Conclusion number 3 is not exactly a conclusion. It's an opinion, or a suggestion. While important and relevant, it isn't based on any analysis or data and hence cannot be presented as a conclusion of the paper. Please rephrase."

Author's response: Following the three reviewers comments we rewrite the entire conclusions section.

"8. Conclusions 1. Mapping and characterizing faults that pose seismic hazard, particularly in regions with intermediate seismicity rates and/or where young formations are sparse, require developing an interdisciplinary regional database and hierarchical seismo-tectonic criteria. With respect to the specific dictated requirements, faults that are potential sources for the far-field and for the near-field (i.e., surface rupture) hazards should be analyzed by different criteria; both represent seismic hazard of significant earthquakes, but within different time frames. 2. We design a seismicity-based criterion that using the distribution of two parameters: the earthquake kernel density and the seismic moment kernel density. The success of this selection is demonstrated by the match between the geological-categorized faults and the seismicity criterion (Fig. A3). The union zone defined by these two statistical distributions is efficient in both definition of the main seismic sources (Fig. A3) and in categorizing capable faults (Fig. 7). 3. The hierarchic seismo-tectonic criteria ideally reflects the degree of certainty for recent faulting, and can later be implemented if a specific hazard is considered or if risk evaluation is applied. 4. The temporal reference for local planning of critical facilities such as dams and nuclear power plants is usually long, because the possible damage to the construction has severe regional implications. We selected the Quaternary period as the relevant time frame for capable faults in the region of Israel. While this time frame (2.6 Ma) is longer than the previous for defining capable faults for a potential local nuclear power plant (IEC and WLA, 2002), it is justified by considering the regional stress field, the regional stratigraphic configurations and the criteria that focus on surface rupture rather than general fault movements. We suggest that tectonic and stratigraphic conditions, as well as the accessibility of geologic maps and their resolutions, should be considered for defining the time frame for capable faults. 5. Beyond planning of special constructions, the developed database and the maps that are generated and presented here constitute further applications for planning and research. The regional main seismic sources map (Fig. 5) is fundamental for seismotectonic modelling and eventually for generating ground motion prediction maps (e.g. by PSHA) that include essential information for construction planning. The capable fault database and the related maps (Figs. 2-4, 6-7) lay the foundation for further

study of the regional Quaternary faulting and tectonics in the Israel region. Furthermore, the methodology, which is based on categorization and sub-categorization by seismo-tectonic hierarchic criteria, enables differentiation of hazard potential and can be applied in other regions around the world. 6. Compering instrumental seismicity with geodetic slip rates enables to reveal seismo-tectonic patterns in an investigated region. Specifically, we recognize along the DST zones of enhanced or reduced seismicity, which can be controlled either by slip partitioning, creep or litho-structural complexities in fault junctions. In addition, ∼NW orientated seismic activity was identified branched from the DST (EBL in Fig. 6). This activity might reflects reactivation of extensional feature developed during the post-Eocene Red Sea rifting. "

9) "Line 296 – the symbol Vs is typically used for shear-wave velocity in the geotechnical earthquake engineering community. I suggest using something else for slip rate."

Author's response: We no longer use this symbol. Instead, we now use a simple "range" (e.g. a – b mm/yr) Author's changes in manuscript:

"these faults are associated with Holocene average sinistral slip rates of 1 – 5 mm/yr."

10) " Line 454 – remove 'many' "

Answer: Removed 11) " Line 455 – 'could have entered the map' rather than enter "

Answer: Corrected

12) "Line 460 – 'Quaternary activity exists'."

Answer: Corrected

13) "Line 462 – siting of what? What is siting? Why is this related?"

Author's response: We rewrite the entire section.

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