Responses to Referee #3

In the following document we provide detailed responses to the different comments and explanations on how we will implement this in a revised version of the manuscript.

Dear editor,

Thanks for the opportunity to review "Coseismic Surface Rupture Probabilities from Earthquake Cycle Simulations: Influence of Fault Geometry" by Gomez-Novell et al. I enjoyed reading the paper; it is well written and makes some interesting points, and in my opinion is worth publishing.

Author's response (AR): We are thankful for the positive feedback on the paper.

I have a few high-level comments that — if addressed — could help significantly improve the paper:

This isn't the first paper to consider RSQSim as a useful tool for PFDHA… The authors should check out Daglish et al. (2025). The present study is much more local in focus and considers impacts of fault geometry, which Daglish et al. do not consider. However, some of the discussion by Daglish et al. may be useful to the authors, especially in the light of my other comments.

AR: We thank the reviewer for pointing out this article, which went unnoticed to us. We will acknowledge this interesting research in two sections of the revised manuscript:

1. Introduction: We will note that Daglish et al. (2025) is the first study to apply RSQSim to FDHA applications and highlight the main differences with our approach to better situate our work within the PFDHA research field.

2. Discussion: In section 4.5 we will emphasize that our results further prove that simulators like RSQSim can be effectively applied to, and may even enhance, PFDHA analyses

The manuscript is overwhelmingly positive about the potential of earthquake simulators for PDFHA… Some detailed discussion of limitation (at least 1-2 paragraphs) would give a more balanced view. For example, I think it's important to discuss uncertainties in trace location, distributed off-fault deformation and the challenges associated with identifying a primary trace.

AR: Throughout the manuscript discussions we acknowledge several limitations of our study. In section 4.2 (lines 474-477 of the original preprint), we discuss how uncertainties in fault traces might be addressed by exploring multiple realizations of fault geometries in line with previous research by Zielke and Mai (2025). We agree that the impacts of not considering off-fault deformation, distributed rupturing or the challenges associated with identifying a primary trace are not addressed in our manuscript. To accommodate this, we will:

1. Detail the implications of not considering off-fault deformation. Our study only tackles one part of PFDHA (primary surface ruptures), which can carry potential underestimations of hazard associated to not considering off-fault deformation and distributed rupturing. In the discussion we will also propose solutions o how these limitations could be mitigated. For instance, the simulated displacements on the principal fault from RSQSim could be used along with approaches like the one from Visini et al. (2025) to develop probabilistic models of distributed fault ruptures.

2. Discuss challenges of identifying primary traces, especially in immature or complex fault zones, and how these limitations might impact our work. Choosing one or other fault trace as the principal will have an impact on the final fault geometry and, consequently, into the simulated catalogues. In relation to what we discuss in section 4.2, we will further highlight the importance of exploring several fault trace hypotheses to capture such uncertainties in the hazard assessments.

The authors are quite evangelical about RSQSim as a simulator and could (ideally) tone down their language slightly throughout the manuscript. I agree that RSQSim does a surprisingly good job generating realistic-looking populations of synthetic earthquakes considering how much it simplifies earthquake physics, but it is only a simple model and is definitely missing some aspects of realistic earthquake slip distributions. The authors should include discussion of the limitations of RSQSim, especially for generating earthquakes.

AR: In section 4.5 we acknowledge that earthquake cycle simulators like RSQSim have important limitations in the physical representation of earthquake rupture processes, especially when compared to fully dynamic rupture simulations (though the comparison is not quite fair, as both approaches serve different purposes). We also discuss in section 4.3 the impact that model parameters such as a-b coefficients or initial stresses have on the simulations. The main advantage of using RSQSim is the balance between computational efficiency and its ability to generate realistic synthetic catalogues, both in terms of long-term statistics and rupture characteristics. We demonstrate this good performance by comparing the simulated catalogues with empirical relations and the simulated coseismic and cumulative slips with field observations. Naturally, discrepancies remain, but these can also reflect processes that have not been considered in the modelling (e.g., erosion, soft sediments, smaller order fault complexities)

Most limitations of RSQSim are already detailed in the original publications by its developers. In the revised manuscript we will moderate some statements on RSQSim's advantages and expand the discussion in the final paragraph of section 4.5.

I know the focus is on the influence of fault geometry, but I think the study should be expanded significantly to understand the sensitivity of surface rupture probabilities to prescribed slip distribution and rake, and the relative importance of those factors compared with fault geometry. For example, I think that the assumed — and largely unconstrained — slip-rate distribution will potentially influence the modelled earthquakes more than geometry. I couldn't find any indication of what rakes the authors specified, but I assume pure normal… Setting a constant horizontal azimuth of extension and adjusting rakes to match that azimuth could also make a big difference to modelled earthquakes. I think those factors are really worth exploring… It is a bit of work but I think it's important and not enough for a separate paper.

AR: We agree with the reviewer that exploring the sensitivity of these parameters would be very interesting, but we do not think it is pertinent for the present paper:

1. The focus of the paper is to evaluate (and isolate) the impact of fault geometry on surface rupture probabilities. Adding more variables to the study, in its current form, will imply major re-design of the modelling set-up and the subsequent analyses. On the one hand, we would necessarily have to enlarge the model sample to accommodate further parameters into the exploration tree. On the other hand, we would not be isolating the effect of geometry anymore. Instead, we would be combining effects and potentially inducing interactions between parameters that might not be trivial to analyse. For instance, some parameters can show non-linear relationships that are not easily identifiable nor quantifiable with the current experimental design. We think these relationships would be rather determined with more advanced techniques like machine learning algorithms (e.g., random forest) that are out of the current scope.

2. The slip rate distribution is not unconstrained, it is informed by surface geological data and follows a tapered pattern towards the fault edges, consistent with observations in the Apennines. Our simulations show that slip rate has a limited effect compared to geometry. For instance, in all connected models, nucleation occurs at depths of segment linkage regardless of slip-rate maxima being deeper. Moreover, the adopted distribution does not prevent long-term slip behaviour to show features that are consistent with observations (e.g., Figs. 11 and 12). While alternative slip-rate distributions could generate differences in the models, our results suggest that their influence is less significant than the reviewer anticipates. The effect of slip rate variability in the simulations is a very interesting and pertinent point, but including it in our study is not pertinent because it would imply major changes in the current experimental design and analyses, and a significant lengthening of the paper. We think that exploring the effect of slip rate can stand on its own as future work, especially considering the uncertainties of this parameter in many regions. In fact, constraining slip rate is a central topic in most fault-based seismic hazard studies, and a dedicated study on this aspect could help address these issues more clearly.

3. We recognize the reviewer's point on the azimuth-adaptive rake; however, we consider it more appropriate not to include it in our analysis, for two main reasons. The first one is that structural studies (e.g., Iezzi et al., 2018) indicate that the slip vector of the Mt. Vettore Fault during the 2016 surface ruptures is for the most part perpendicular to the fault strike along the fault trace, only oblique in the northern sector of the Vettoretto Redentore segment. Second, the exploration of a geometry-dependent rake would generate significantly different rake fields across the models. These model differences could interfere with strictly geometry-related features in the catalogue, ultimately interfering with the analyses that we present.

I'm worried by the way slip-rate distributions are specified… Delogkos et al. (2023) tapered slip towards the edges of each fault segment, whereas this study tapes across the whole fault segment. I think that combined with the loading scheme, this approach will potentially lead to nucleation of very large (unrealistic) numbers of small earthquakes close to fault edges. That effect may be negated in the analysis by the minimum of 10 patched that the authors impose, but it is important to provide better visualisation of where earthquakes nucleate in the model, either in the main paper or supp info.

AR: We appreciate the reviewer's concern with the slip rate distributions adopted in our study. There are a few key points that justify our decision:

1. Consistency across models: Applying a whole fault tapering approach ensures comparability between the different geometric configurations explored. If we tapered at the edges of individual segments, this would lead to significantly different slip rate distributions between disconnected and connected models – particularly at depth. Different slip distributions across the fault planes would necessarily produce divergences in peak values, since they are scaled so that the average for all fault elements equals 1 mm/yr. This could introduce variability between catalogues linked to the imposed slip distribution, potentially obscuring the variability that is strictly geometry-related.

2. Geological constraints: Linking with our response to reviewer #1, the slip rate distribution is designed to reflect surface geology (e.g., 1mm/yr in the central part of the fault), while keeping it simple enough to avoid overfitting to localized slip complexities recognized in literature, which often reflect site-specific effects (e.g., fault bends).

3. Focus on geometry control: One of our aims was to test whether the observed along-strike slip variability, like cumulative slip reduction at the segment tips, could emerge from fault geometry alone. A simplified slip rate distribution allows us to isolate geometric influence on the final slip of the models.

4. Consistency with higher order structure: The Mt. Vettore fault, although segmented, is regarded as a single higher order fault structure. Even though the relationship of these segments at depth is not clear, we wanted to adopt a slip rate distribution that reflects the large-scale structure of the Mt. Vettore fault, rather than imposing slip rate tapering that we do not know how resolves at depth.

As the reviewer anticipates, there are earthquake nucleation artifacts at the segment tips in our models. But these have a limited impact in our analysis.

A. Impact on surface rupture regressions:

Most of these nucleations correspond to low magnitude earthquakes (Mw 4-5), as illustrated in the figure A (see below) for the two end member connectivity models. Their frequency decreases markedly for Mw>=5, and since Mw<5 earthquakes rarely generate surface ruptures, the effect of such artifacts on the regressions is likely unnoticeable.

In addition, hypocentral depths of these artificial Mw 4-5 nucleations (6-9 km; Fig. B) are consistent with depth distributions of real earthquakes in the Apennines. This indicates that shallow, fault-edge nucleations are proportionally uncommon, further limiting any potential bias in the surface rupture probability regressions (depth of nucleation is a big factor controlling surface rupture likelihood).

B. Impact on spatially variable surface rupture probabilities:

Spatially variable surface rupture probabilities for Mw ≥ 6 (Fig. 10 of the paper) are primarily controlled by the along-strike slip rate distribution and fault geometry. Local probability increases at segment boundaries may partly reflect minor nucleations near fault edges (Fig. A, right column), but they are also explained by geometric complexities (such as bends or deep segment connections) that promote earthquake nucleation (also seen in Fig. A). This is consistent with previous observations; for instance, Lavecchia et al. (2016) documented that the 2016 Mw 6.0 Amatrice earthquake nucleated at an intersegment zone where two faults link at depth.

Importantly, the key outcome of PFDHA is the probability of exceeding a slip value at a site over a given time span, which depends on that site's slip history. Thus, even if surface rupture probabilities are elevated at the segment edges, the hazard is ultimately governed by the coseismic slip recorded in these regions (especially with the displacement approach). Our models show that both coseismic and cumulative slip taper toward segment edges (Figs. 11 and 12), independent of nucleation location. This suggests that localized increases in surface rupture probability are unlikely to bias fault displacement hazard, since these regions contribute less slip.

In the revised version we will include the figures shown here as Supplementary information and we will add the discussion described above.

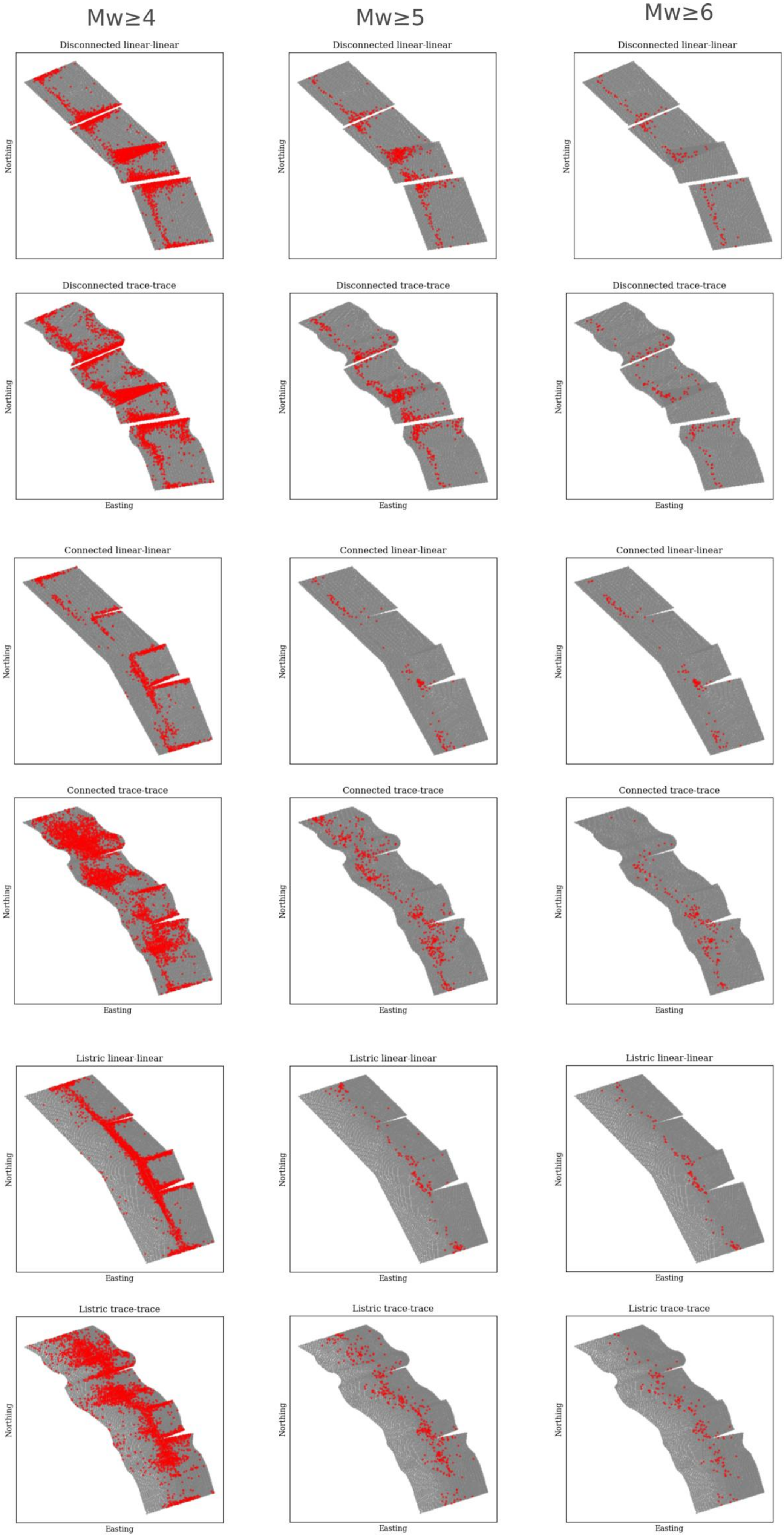
Mw≥4
Mw≥5
Mw≥6
Disconnected linear-linear
Disconnected trace-trace
Connected linear-linear
Connected trace-trace
Listric linear-linear
Listric trace-trace
Northing
Easting

Fig. A

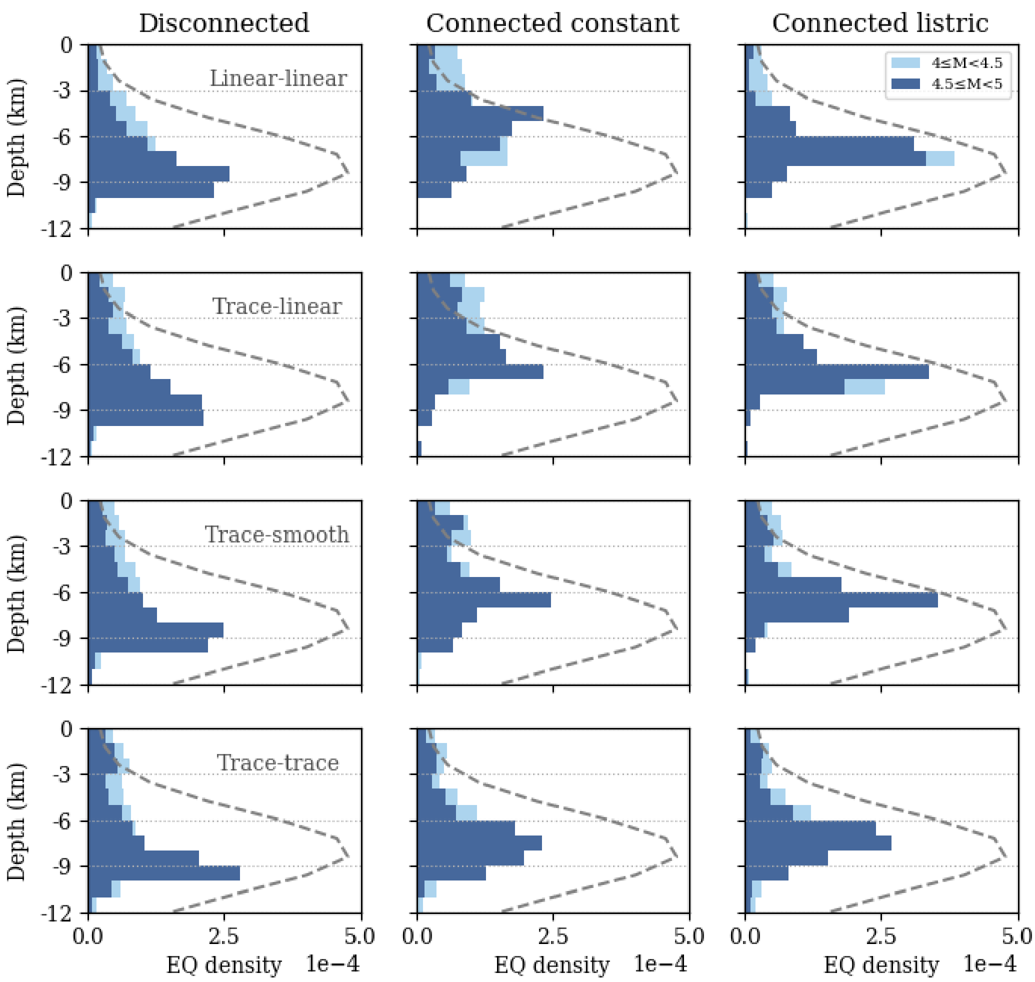

Fig. B

References mentioned:

Iezzi, F., Mildon, Z., Faure Walker, J., Roberts, G., Goodall, H., Wilkinson, M., Robertson, J. Coseismic throw variation across along-strike bends on active normal faults: Implications for displacement versus length scaling of earthquake ruptures. Journal of Geophysical Research: Solid Earth, 123, 9817–9841. https://doi.org/10.1029/2018JB016732, 2018.

Lavecchia, G., Castaldo, R., De Nardis, R., De Novellis, V., Ferrarini, F., Pepe, S., Brozzetti, F., Solaro, G., Cirillo, D., Bonano, M., Boncio, P., Casu, F., De Luca, C., Lanari, R., Manunta, M., Manzo, M., Pepe, A., Zinno, I., and Tizzani, P.: Ground deformation and source geometry of the 24 August 2016 Amatrice earthquake (Central Italy) investigated through analytical and numerical modeling of DInSAR measurements and structural-geological data, Geophysical Research Letters, 43, https://doi.org/10.1002/2016GL071723, 2016.