Reply to the comments of the Reviewer #1

A: We thank the Reviewer for a comprehensive review of the manuscript, his/her valuable comments and an overall positive evaluation. We respond hereafter to the specific comments of the Reviewer and point out, how we would tackle the raised issues in the revised manuscript.

R: The Authors have studied fluvial dikes along the river Rhine nearby Cologne (Germany) under combined seismic and flooding loads. The manuscript contains: multi-hazard fragility analysis and damage risk (failure probability) analysis. It represents an interesting interdisciplinary research, which perfectly fits in with the scope of NHESS. The topic is timely and innovative.
Although the text is generally very well written (it is virtually word-perfect), the style is slightly verbose. There is room for considerably shortening the manuscript by focusing more strictly on the key messages and avoiding redundancy. For instance, the text on P7 (comments of Figs. 3; 4 and 5) is unnecessary long, …

A: We would revise the manuscript in in this regard, shorten the figure captions and remove redundancies.

The literature review is comprehensive.
It seems that the Authors focus solely on "liquefaction" of the dike (based on Seed and Idriss, 1971), while worldwide dike overtopping is by far the most frequent mode of dike failure. A discussion is needed in this regard.

A: The reviewer is right that the overtopping seems to be most frequent dike failure mechanisms, as statistics collected by Vorogushyn et al. (2009) shows. However, the methodology for development of fragility curves for overtopping has been already presented by Apel et al. (2004) and to our knowledge is still based on the best available process knowledge considering data availability. Vorogushyn et al. (2009) developed methods for piping and micro-instability failure mechanisms. Though liquefaction is not very common, this is a likely breach mechanism under multi-hazard load by floods and earthquakes. Such fragility curves would thus be required for multi-hazard assessment of dikes in earthquake-prone areas. We shall point out in the manuscript more clearly to the previous developments in the field and the purpose of the presented methodology.

Wording "damage risk" sounds a bit odd. If I understand well, the authors use the word "risk" for "probability", since they mean actually the "probability that some damage occurs" (elsewhere, they use "damage probability", e.g. in Sect. 3, in title 15 of Sect. 4 …). In science and engineering, risk is a broader concept than just "probability". It would be wiser to consistently use the wording "failure probability" throughout the manuscript, instead of "damage risk".

A: We agree with the reviewer that the term "damage risk" can be misleading and shall substitute it with the term "damage or failure probability". This is actually what we mean in the presented context.

Clarifications are necessary regarding the derivation and characteristics of the fragility surface displayed in Fig. 3. Why does the failure probability not reach 1 for the highest values of water level (e.g. overtopping or nearly overtopping conditions) when PGA is low or zero? The same applies for Fig. 4. The reason relates probably to the liquefaction mechanism which is considered by the Authors; but still the results seem a bit puzzling.

A: Yes, the reviewer is right. The probability of dike failure/damage does not reach 1 even for water levels reaching the dike crest at low values of peak ground acceleration (PGA). At the first glance it looks odd, but if we recall that under probability we mean solely the probability of failure due to liquefaction and not the overall probability of dike failure then this result appears meaningful. We shall briefly explain this in the revised manuscript.

2 Specific comments
In the Introduction, mention the different failure mechanisms of dikes (incl. overtopping, seepage …) and briefly discuss their relative importance.

A: We shall do so.

Make clear which are the differences between *embankments* (frontal / normal to the flow direction) and *dikes* (parallel to the flow direction), and which are the consequences in for risk analysis (different designs, presence of a core …)?

A: It seems that the term 'embankments' is sometimes used as a synonym for dikes/levees. However, "embankment dams" are meant indeed as structures frontal/normal to the flow direction. In the manuscript we refer at some occasions to the literature on "embankment dams". We shall carefully check the use of this term, prove the consistent use and explain the difference as suggested by the reviewer.

Explain the complementarity between "large scale" studies such as the present one and more detailed small-scale studies (e.g. Rifai et al. 2017, WRR). While the latter are interested in the fine details of the failure mechanisms, studies such as the present one provide valuable insights on the effects on dike failure at a much broader spatial level (regional).

A: Thanks for this comment. We shall "bridge the scale" by linking small scale process studies to the attempts of applying the knowledge at a larger scale. This is actually what the presented manuscript tries to do: use the detailed geotechnical process knowledge to derive fragility curves which can be used for large scale risk assessment and modelling studies.

☐Define "hazard curve".

A: Shall do so.

☐Is the wording "impoundment of the dike" standard in the field? It sounds a bit odd compared to more standard terminology such as "overtopping" or "overflowing" of the dike …

A: The literature in the field is not very numerous. So, it is hard to say what is standard though the term was already previously used. "Impoundment of a dam" would be more obvious. With a dike the situation is different, since the flow is usually parallel to the dike. But we still believe, the term "impoundment" would be appropriate since we explicitly do not mean "overtopping" or "overflow" of a dike, but also consider the situations, where a dike is only partially "impounded" by water, i.e. the water level does not reach the crest by far.

☐Explain shortly "overburden stresses", as the readership of NHESS is multidisciplinary.

☐Is "phreatic surface" a standard terminology in English? Does it stand for "water table"?

☐Table 1: explain "N-values", "blows/foot".

☐Acronym PGA must be clearly defined when it is first used.

☐P6 L28: is the word "proportional" (i.e. a purely linear relationship) appropriate?

A: We shall address the previous minor comments.

☐Fig. 3 and Fig. 4 seem redundant … They display the same information, don't they?

A: In fact, yes. Figure 4 represents the contour plots in the PGA-Water level 2D space of Figure 3. This is because 3D plots are sometimes difficult to interpret, but they nicely show the 3D nature of the fragility surface.

☐P8 L9: why disregard more frequent floods than the 100-year flood?

A: Yes, in fact, one can consider also smaller floods as soon as the dikes become impounded. This comment refers, however, to the future modelling study building upon the presented manuscript.

☐P8 L15: explain briefly "S-wave velocity" for he multidisciplinary readership of NHESS.

A: Thanks, we shall do so. Surely, for the flood research community, the earthquake-specific terms are not necessarily known.

☐P8 L33: is the word "risk" appropriate there?

☐P9 L13: replace "term of the equation" by "factor in the integral".

☐P9 L17-19: remove this paragraph as it sounds trivial.

☐P10 L17: "at" instead of "it"

☐P10 L23: "uppermost" instead of "most upper"

A: The minor issues above will be edited.

☐Fig. 6 : the caption must explain that each curve corresponds to a different dike section. Using a grey scale (or colors) for the different curves would make the graph more informative by suggesting which curves correspond to more upstream (resp. downstream) dike sections.

A: thanks, we shall try to implement this suggestion and see if the outcome is better readable.

☐Conclusion: please shorten. There are some repetitions, particularly in the second half of the Conclusion.
A: Yes, we shall do so.

3 Formal issues, typos …

A: We shall properly address the small minor issues listed below

☐P5 L9: “there are different methods exist” … Rephrase.

☐P5 L11: remove “engineering”

☐P5 L25: remove “to be”

☐P6 L20: “in three-dimensional form”, instead of “in the three-dimensional form”

4 Conclusion

I strongly recommend that the Authors are invited to submit a revised version of the manuscript for publication in NHESS. I believe that substantially shortening the text, by focusing on the main points, would enhance the potential impact of the paper. If necessary, I am available to review the revised manuscript.