Reply in response to Journal reviewer 2 comments of

“Mid-field tsunami hazards in greater Karachi from seven hypothetical ruptures of the Makran subduction thrust”

a manuscript by Haider Hasan, Hira Ashfaq Lodhi, Shoaib Ahmed, Shahrukh Khan, Adnan Rais, and Muhammad Masood Rafi submitted for publication in *Natural Hazards and Earth System Sciences* (nhess-2024-110)

Revised manuscript title

“Mid-field tsunami hazards in greater Karachi from hypothetical ruptures of the Makran subduction thrust”

We appreciate the feedback Reviewer 2 has provided on our manuscript. The review has highlighted several important areas for improvement. However, we would like to bring to your attention that Reviewer 1 accepted the paper for publication with minor revisions, citing its well-written nature and robust methodology as key strengths and the contributions of our study to the field. Reviewer 1’s comments focused on specific enhancements, which we are already addressing.

Moreover, we understand Reviewer 2’s concern about the length of the manuscript, it is primarily due to the inclusion of extensive figures and appendices that are integral to the study. This length has not been an issue for Reviewer 1 and as such, substantial reductions are not feasible without compromising the completeness of the results presented.

In contrast, some of the concerns raised in Reviewer 2’s response appears to be in direct contradiction with the feedback from Reviewer 1. For example, while Reviewer 1 found our approach and results to be well-presented and methodologically sound, Reviewer 2 suggests that there are significant issues with our concept and methodology. It is important to note that many of these concerns relate to the presentation and clarification of our method rather than inherent flaws in the approach. To ensure that we address all concerns comprehensively, we have provided a point-by-point response to your comments and concerns.

1. *The article analyzes mid-field tsunami hazards. However, the concept of “mid-field” is presented rather vaguely. This concept is relative to “far-field” and “near-field”, but the authors lack a clear definition in terms of distance. Moreover, they do not explain the significance of using this concept for disaster prevention. Compared to near-field events, are there any specific characteristics of mid-field tsunami propagation that need attention? How would it differ in causing inundation?*

   The introduction of the "mid-field" concept within this paper has not been used in tsunami hazard studies before, thus we recognize that its definition requires further clarification. Below we address the points raised which will help to improve upon this concept in the revised Introduction section of the manuscript.

Clear Definition of Mid-Field

The mid-field zone refers to coastal cities that are neither in the near-field (typically defined as locations where shaking from the tsunami-generating earthquake is strongly felt, usually within 100-200 km of the rupture and/or wave arrivals are within one hour) nor in the far-field (where the arrival of tsunami waves is delayed by three hours or more, often with the rupture around thousand or more kilometers away) (IOC, 2019; Wood and Council, 2011). Mid-field cities lie in an intermediate zone, where the tsunami is expected to reach in between 1 to 3 hours. While they are close enough to experience significant tsunami hazards, they are often too far from the rupture to feel strong seismic shaking. This absence of shaking can lead to a dangerous underestimation of the tsunami threat, as local populations may not receive the natural warnings that near-field communities experience. This also means that the population in the midfiled has to rely on timely dissemination of tsunami early warning by the authorities.

Significance for Disaster Prevention

The mid-field concept is critical for disaster preparedness because these cities, including places like Karachi, have limited lead times (often 1 to 3 hours) before the tsunami waves arrive. While far-field cities benefit from extended warning periods due to the longer travel time of tsunami waves, and near-field cities can rely on earthquake shaking as a natural alarm, mid-field cities may neither feel significant seismic activity nor have sufficient time for effective evacuation or disaster response if early warnings are delayed. Therefore, the introduction of mid-field is significant for improving hazard assessments, preparedness, and response strategies tailored to such locations. The paper underscores that current tsunami warning systems must be adapted to consider mid-field locations more rigorously to avoid underestimating the risks faced by these cities.

Characteristics of Mid-Field Tsunami Propagation and Inundation

In terms of tsunami propagation, mid-field cities typically experience the first waves within 1 to 3 hours of the rupture event, depending on their proximity to the source. These waves can often be higher and faster than those reaching far-field cities, but arrive without the natural warning signals that near-field cities rely on. As a result, mid-field cities need special attention in terms of evacuation planning.

For example, the simulations in our study show that for Karachi, the tsunami waves from a large rupture in the Makran Subduction Zone arrive at Karachi Port in 1.5 hours, whereas Port Qasim (∼30 km east) experiences waves almost 3 hours later. This indicates that mid-field cities experience significant variability in arrival times and wave heights depending on local topography and coastal geography. Inundation in mid-field cities may differ from near-field events, primarily due to longer wave travel times, which may allow the tsunami to disperse somewhat, but the inundation in low-lying areas can still be severe, as shown in our simulations of Karachi. For example, flooding can extend farther inland into residential zones without seismic shaking to prompt early evacuation.

2. *The selection of the seven cases in the article appears somewhat arbitrary. This study considers a maximum magnitude of up to 9.2, but it lacks a discussion on the probability of such an earthquake occurring. The author should at least clarify the magnitude represented by each case (Figure 3). If the intention is to select randomly, I suggest the author consider using the PTHA method, rather than focusing on the worst-case scenario.*

   In response to this comment, we have provided a clarification below, which will be used to improve upon the section related Numerical model setup.

   The approach used in our paper is based on Deterministic Tsunami Hazard Assessment (DTHA), with the focus on the largest possible events rather than estimating their probabilities. This method is useful in regions where historical data is insufficient to model event probabilities accurately, such as the Makran Subduction Zone (MSZ), where the recurrence intervals for large tsunamigenic earthquakes remain poorly understood. DTHA remains highly relevant for emergency planning, as it helps authorities plan for the maximum possible risk. This approach is similarly applied in other countries, including the United States (Dolcimascolo et al., 2021; Garrison-Laney et al., 2021) and Indonesia (Adityawan et al., 2023),where worst-case scenario modelling plays a critical role in hazard mapping and disaster management.

   In line with the Sindh Tsunami Management and Response Plan (Provincial Disaster Management Authority (PDMA) Sindh, Not dated), our study emphasizes a worst-case scenario analysis, aligning with the approaches utilized by national authorities like the study by Pakistan Meteorological Department (PMD) discussed in the report by Mahmood et al., (2012). The Plan underlines the significant risks posed by a potential tsunami from the Makran Subduction Zone (MSZ) to Pakistan's coastal regions, particularly in densely populated areas such as Sindh, where the tsunami waves could reach the coast within a short timeframe. Given the substantial development and population growth since the last major tsunami in 1945, focusing on a worst-case scenario ensures that disaster preparedness, response planning, and mitigation efforts are sufficiently robust and tailored to the most severe potential impacts. Notably, both the Pakistan Meteorological Department (PMD) and the Provincial Disaster Management Authority (PDMA) utilize the deterministic approach, like our study, to inform tsunami risk assessments and enhance early warning systems.

   In this context, the work by Adityawan et al. on the Palu region of Indonesia also consider the application of DTHA, particularly in areas where there is insufficient seismic data to model recurrence probabilities. Their research, which focuses on developing a tsunami early warning system based on maritime wireless communication, used numerical modelling of worst-case earthquake scenarios to enhance disaster preparedness. Like our approach, Adityawan et al.

emphasized the importance of focusing on worst-case scenarios in order to optimize early warning systems and improve mitigation strategies. Therefore, while PTHA offers important insights, our use of DTHA aligns with both international practices and the Sindh Tsunami Management and Response Plan.

Further, it is crucial to clarify that the selected scenarios are not arbitrary. They are based on a thermal modelling study conducted by Smith et al. (2013), which indicate the potential for megathrust earthquakes in this region. The scenarios reflect credible worst-case conditions derived from known tectonic characteristics and documented events. Specifically, the maximum magnitude of 9.2 is informed by Smith et al.'s thermal modeling, which suggests the possibility of a full-length rupture of the MSZ.

As suggested, we will annotate Figure 3 to specify the magnitude associated with each case and additionally, we will add a column to Table A3 to include the moment magnitude (Mw) for each scenario.

3. *There is some lack of clarity in the method description, such as the absence of a clear definition for arrival time. I also hope the author can explain why the presence of splay faults would result in the run-up doubling (Line 155). What is the reason behind this?*

   It appears that the concerns raised here are more about specific terminologies and details in the literature review rather than the overall method description.

   Firstly, regarding "arrival time," this term refers to the time it takes for the maximum wave to reach the coast after the tsunami is generated, as determined by our numerical simulations (line 283). We will update the text so the definition of "arrival time" is clearer at the outset in the manuscript.

   As for the statement about the doubling of run-up heights due to splay faults, this is a finding from the study by Heidarzadeh et al. (2009a), cited in the literature review (Line 155). Splay faults are secondary fault structures that branch off the main fault and cause additional vertical displacement during an earthquake. This vertical movement increases the tsunami's energy and can lead to a doubling of the run-up heights as observed in the study. It should be noted the splay faults are not considered within our study, however, we will revise the manuscript to make this conclusion from Heidarzadeh et al. clearer.

4. *Figure 7 compares the simulated values with the records of the 1945 tsunami, yet the whole figure is perplexing. The negative phase of the blue curve (simulation) shows a significant truncation, which is caused by the wet point depth of the bathymetry and can introduce substantial errors.*

   The negative phase of the blue curve (simulation) reflects the drawdown to the level of the modern tidal flat. This is clearly indicated in the figure. GeoClaw, the software employed in this study, is adept at modelling wetting and drying processes thus ensuring accurate simulation of such effects. Given GeoClaw's capability to effectively handle such interactions, we believe that this aspect of the simulation will not introduce substantial errors.

5. *There are spelling issues throughout the entire article, with quite a few typos and grammatical errors. I suggest that the author thoroughly proofread and polish the text before resubmitting.*

   We will thoroughly review the manuscript to address all spelling, typographical, and grammatical errors.

6. *Line 32: "December 20011"?*

   Will make the correction

7. *Line 52: What do you mean "unseen"?*

   By "unseen," we mean events that were not anticipated or previously experienced at those locations. Both the 2004 Sumatra-Andaman earthquake and the 2011 Tohoku earthquake occurred in regions that had not been historically associated with such large, destructive events.

8. *Line 102: What is the meaning of "dwarf"?*

   The term "dwarf" here means the proposed fault rupture widths of 210-355 km are much larger than the 1945 rupture width of 100-150 km, making it seem smaller in comparison.

9. *Line 181-185: This section seems to deviate from the main topic; I suggest deleting it.*

   The issues with the tide gauge during the 1945 tsunami, such as mechanical failures and sediment blockage, are crucial for understanding limitations in historical tsunami data. Including these details in the "Tsunami Modelling" section highlights challenges in interpreting historical records and underscores why some data may not align with model predictions. This context is essential for appreciating the complexities of tsunami modelling and justifies the need for accurate data collection and modelling improvements.

References

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