Annex 4.3: Summary report on the development of the PTHA (Version 1.0)

Workshop on Makran Subduction Zone Science Strengthening Tsunami Warning and Preparedness

The UN ESCAP TTF 29 project "Strengthening Tsunami Early Warning in the Northwest Indian Ocean Region through Regional Cooperation" aims to enhance national end-to-end tsunami warning systems in the NWIO region, especially to strengthen self-protection capacities at the community level.
In particular, a better understanding of the tsunami hazard of the Makran subduction zone has been achieved through detailed PTHA modelling. The PTHA model is the first of its kind in the region. It provides a much-needed dataset that will be utilised for modelling scenarios of local tsunami inundation that will inform community evacuation maps. This summary report gives the first results of a small working group of experts which was presented during a Science Workshop in Abu Dhabi, 14-16. November 2022. A detailed report/publication is in preparation

Introduction

The arguments in this introduction are in most parts following arguments made by Giblin et al., 2022. Earthquake-generated tsunamis represent an important fraction of the hazard; around 75% of historical tsunamis were generated by earthquakes. PTHA is a methodology that can be used to estimate the average frequency of tsunamis which might be of importance for disaster risk reduction. For example, we might want to estimate the average frequency of tsunami inundation exceeding some depth (such as >1m) at a specific coastal site of interest, where people or infrastructure will be located. Because tsunamis are rare, usually only limited data is available to constrain the hazard, and the frequency of inundation is often uncertain. A benefit of PTHA is to integrate these uncertainties into the results, which is important because uncertainties should have an influence on robust risk-management decision-making (Behrens et al. 2021).

PTHA is much better established for earthquake tsunamis than for tsunamis from other sources (Behrens et al., 2021). In particular, for earthquake tsunamis, large-scale PTHAs exist for different ocean bains that provide a basis for earthquake-tsunami scenario design for site-specific tsunami hazard assessments. PTHA for non-earthquake sources are much less advanced than for earthquakes (Behrens et al., 2021). Some progress has been made for landslides and for some volcanic mechanisms. But to the authors' knowledge there are no corresponding large-scale PTHA databases that can support tsunami scenario design for inundation hazard assessments.

Probabilistic Tsunami Hazard Assessments (PTHAs) are designed to estimate the frequency with which tsunamis of any given size may occur in the future. Although we cannot predict the timing of future tsunamis, nor precisely how often they occur, PTHA enables their average frequency to be estimated with quantified uncertainties. This is useful to support emergency management planning and risk mitigation.

The largest and most destructive tsunamis occur with the lowest frequency and therefore coastlines with significant tsunami hazard may not have a historical record of tsunamis comparable to a credible worst case. Because tsunamis are often not well represented historically, the tsunami hazard is often very uncertain (Behrens et al., 2021). For example, prior to the 2004 Sumatra–Andaman earthquake which generated the Indian Ocean tsunami, the historical record did not suggest that such large earthquake tsunamis were possible in the Sumatra–Andaman region. However, there had been some speculation that very large earthquakes and tsunamis might be possible, based on consideration of uncertainties in the regional historical record (Cummins, 2004). PTHA provides a framework where such uncertainties can be integrated into the analysis. This is advantageous because it can facilitate more robust hazard assessment to inform risk mitigation (Behrens et al., 2021).

In principle, PTHAs involve the simulation of a large set of tsunami scenarios that are intended to represent the full diversity of tsunamis that may occur in the future. This is a significant undertaking and in practice, PTHAs may limit the scope to regionally significant earthquake sources, or to major earthquake sources at ocean-basin or global scales.

The intention of PTHA is to estimate the frequency of tsunamis of any given size, and to represent the uncertainty in these frequencies. The advantage of PTHAs for onshore hazard assessments is that the site-specific studies do not need to perform their own analysis of tsunami scenarios, frequencies and propagation simulations but can utilize PTHA databases. This saves time and promotes greater consistency between different studies.

In the case of the North-West Indian Ocean the PTHA (Version 1.0) was done comprising seismic sources in the Arabian Sea (Makran Subduction) and for the first time the Persian Gulf and the entire Red Sea. The Analysis was performed by an international team of scientist from Germany, Italy, Norway and India with support by scientists of Iran, Pakistan, Oman and UAE. A lot of work has already been done for the Arabian Sea, especially the Makran subduction (see Literature) but this study aimed to be inclusive for the whole region and to provide a consistent and sustainable database for future use in e.g. inundation modeling for coastal risk analysis or evacuation planning. Important to note that the scientist from Germany, Ital and Norway are part of the Global Tsunami Model (GTM)

Results as presented during the Abu Dhabi Science Workshop 14-16 November 2022

Starting point of the PTHA is the study by Issa El-Hussain et al. in 2018 who developed a seismic source model for the Arabian Plate. In this work they divided the region in 75 seismic zones (Fig. 1) and determined earthquake parameters like recurrence parameters or M_{max} values for each zone.

In this study a grid of synthetic seismic sources was generated with a grid spacing of 25 km (Fig. 2). Along the coastlines so-called points of Interest (POI’s) have been defined at a water depth of 50 m (Fig. 4). For these POI’s the wavehight of tsunami from each synthetic source constructed for a range of magnitudes and other source parameters has been calculated by running respective tsunami propagation. In this manner the whole region and thereby the area seismicity was covered.

By assigning recurrence probabilities, magnitude exceedence probabilities and other constraining parameters to the sources we finally reach at a probability distribution for possible tsunami hights at every POI and from these distributions hazard curves can be determined giving the probability for the exceedence of a given tsunami wavehight per year. On the other hand especially for risk calculations and assessments one might be interested in the maximum waveheights to be expected in a give time interval.

Figures in the following are taken from the presentation of Andrey Babeyko, GFZ Potsdam, held at the Science Workshop in Abu Dhabi on 15. November 2022

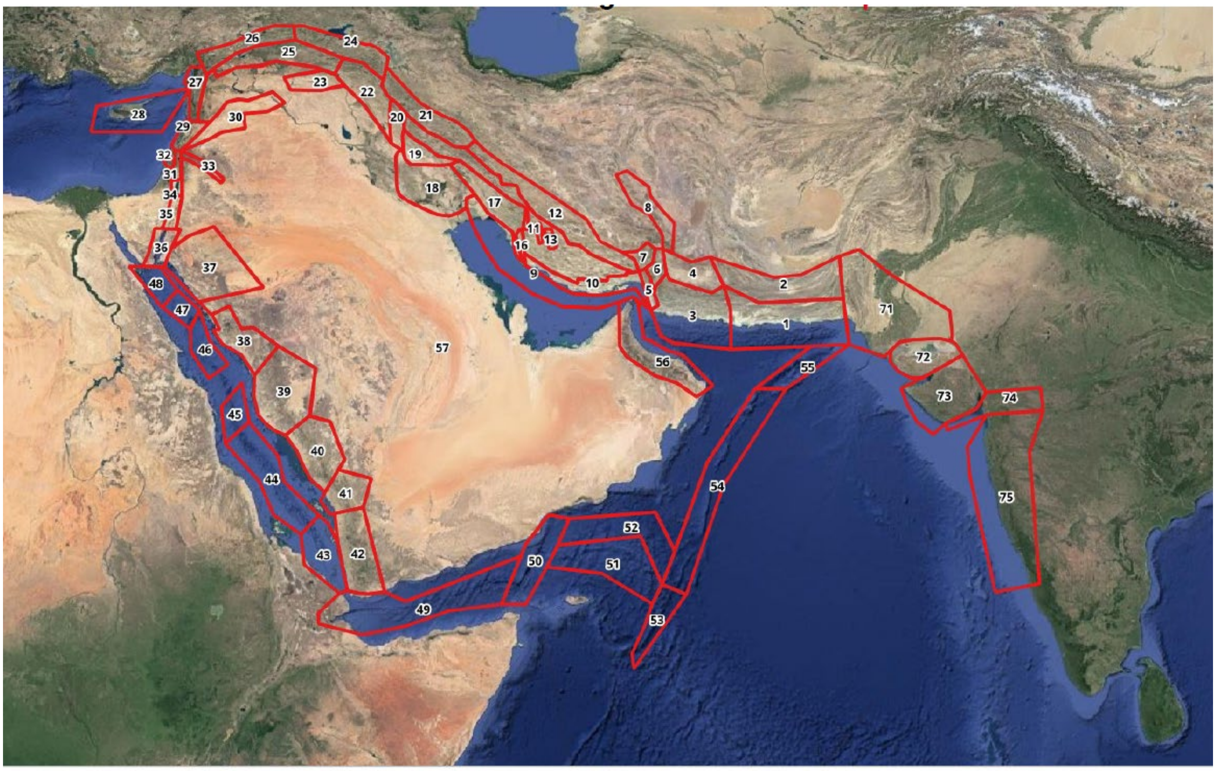

Fig. 1: Seismic zonation of the Arabian Plate

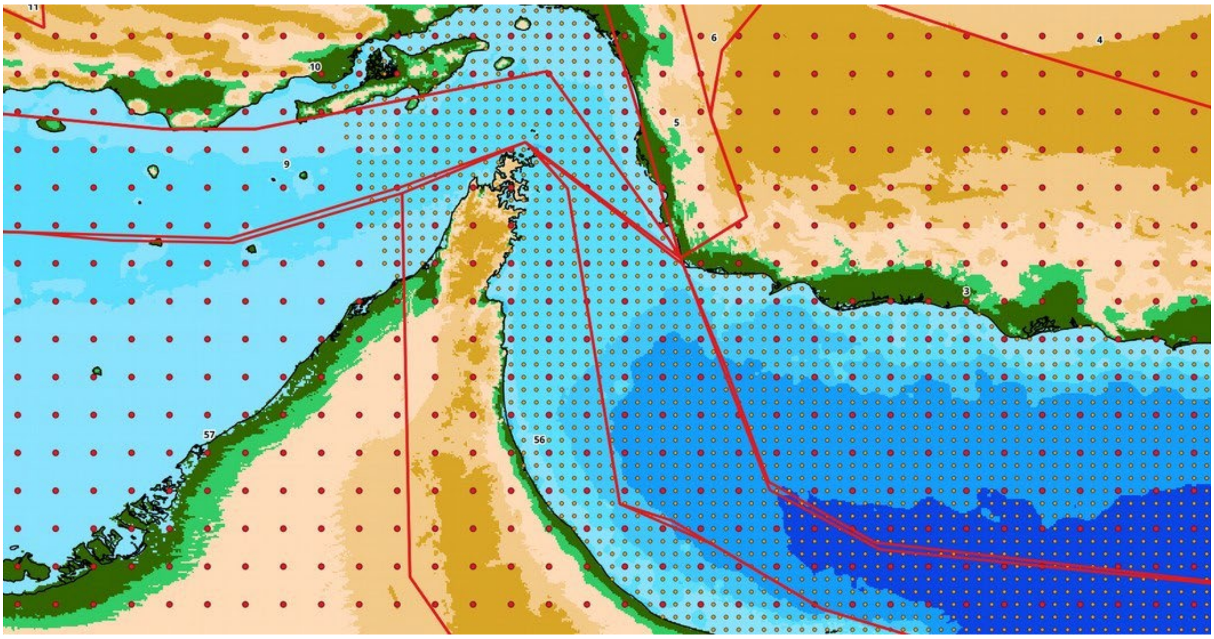

Fig. 2: Grid for the seismic source calculation (Zoom). Distance of grid points: 25 km
Per centre and magnitude following parameters are varied:

- depths: [5, 15, 35] km
- strikes: each 45°
- dips: [15, 45, 60, 90]
- rakes: [0, 90, -90]

This results in 288 scenarios per centre and about 5.000.000 scenarios in total

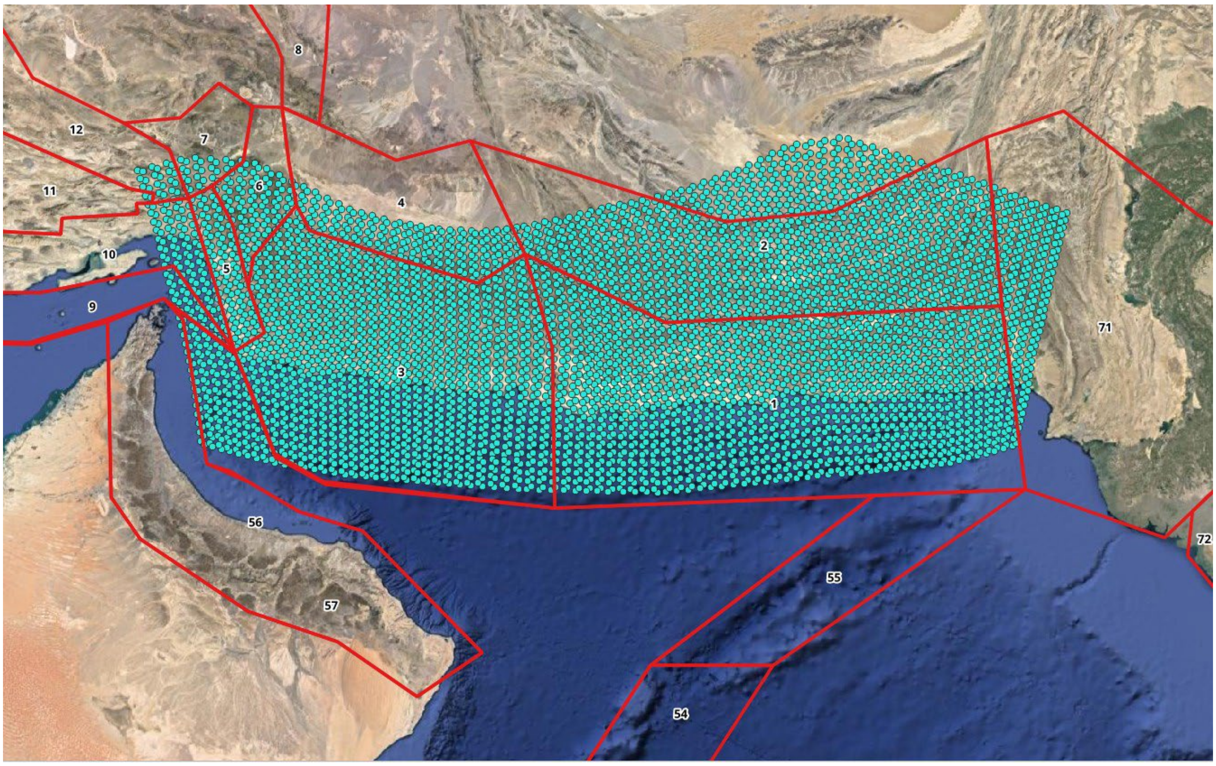

Fig. 3: Diskretisation of the Makran subduction interface, variation of magnitudes from 6.0 to 9.1 results in 120.000 scenarios

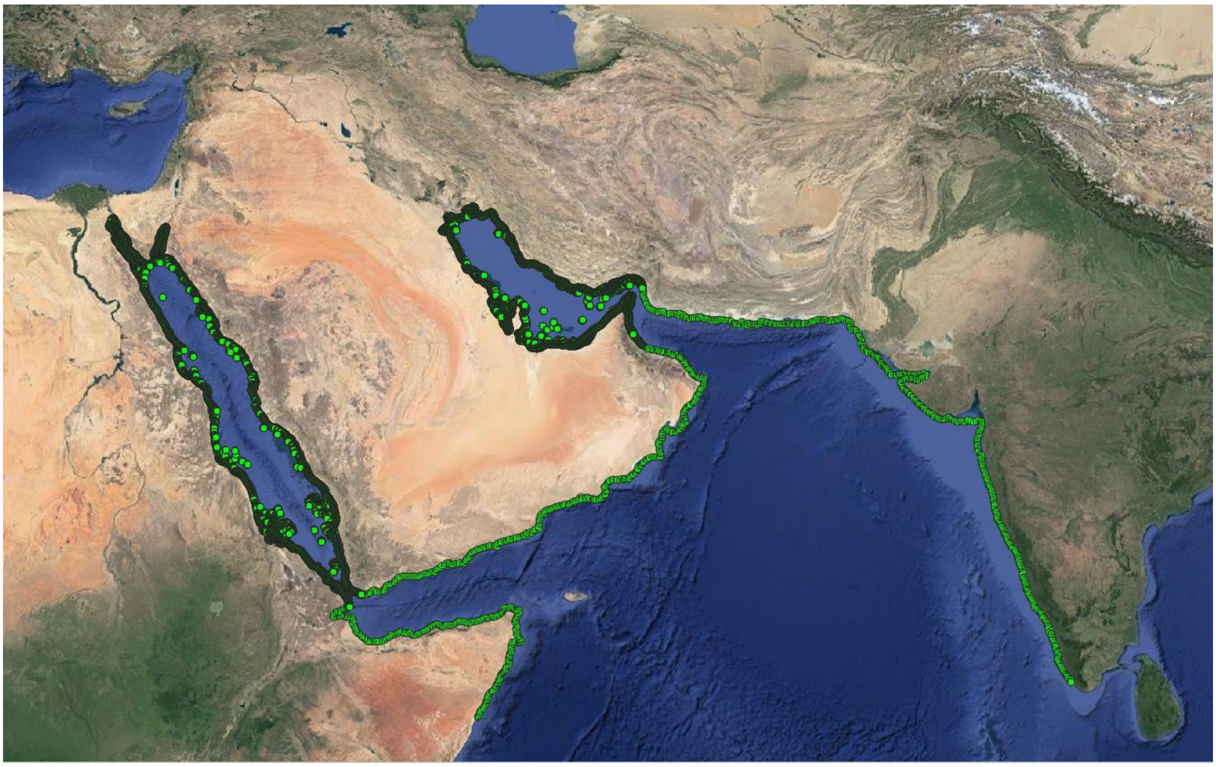

Fig. 4: Distribution of POI's: Arabian Sea: 1110; Persian Gulf: 11255; Red Sea: 17407 (Black line due to high density of POI's)

In order to demonstrate the possibilities, two models have been adopted, which are shown in the table

Model 1	Model 2
BS as in PSHA	BS: M_{max} + 3sigma
PS: Makran zone segmented as in PSHA M_{max} = 6.2 for West-Makran and M_{max} = 8.4 for East-Makran)	PS: Makran zone unsegmented M_{max} = 9.1

Below two example results are shown that can be obtained in a simple way using the results of PTHA which are stored in a database. In the first example (Fig. 5), for model 1 of the table, the scenario M_{max}=8.4 has been explicitly selected for the eastern part of the Makran zone together with the background seismicity from the PSHA (El-Hussain, 2018) with the presented results (wave heights) at the POI's.

In the second example (Fig. 6), the results from the PTHA have been taken for a recurrence period of 2500 years and the wave heights expected during this period have been plotted according to model 2 of the table. One can see a clear difference, which is simply due to the fact that the recurrence period for the very strong earthquakes in the macrane zone (m> 8.5) are above the selected period and therefore they are not considered in the probabilistic view.

Therefore it is always necessary to have a discussion between the scientists and the disaster managers when it comes to the decision what scenarios shall be taken for planning processes, which risk one wants to take and which consequences one actually wants to bear.

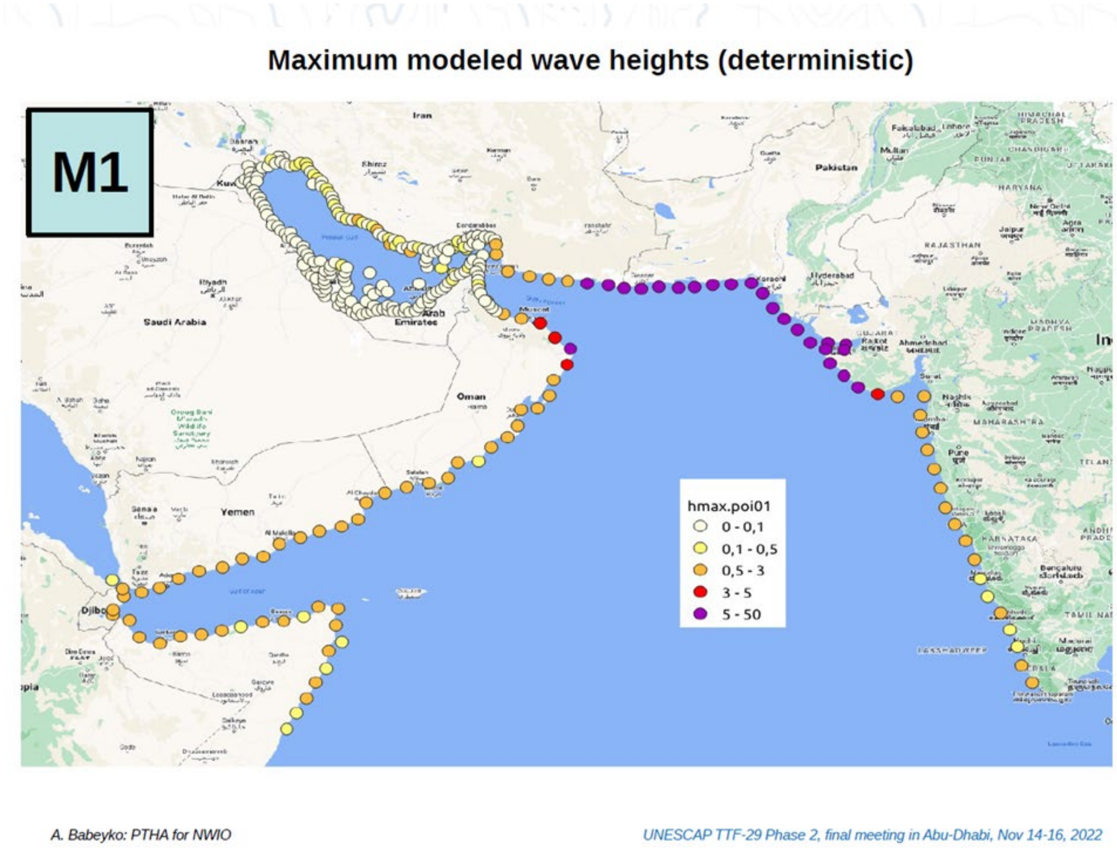

Fig. 5: Maximum modeled wave hights using model 1 (deterministic)

Fig. 6: Maximum expected wave hights in 2500 years (probabilistic)

Conclusions

- PTHA includes sources besides the Makran subduction: all possible crustal sources along the Arabian and Red Seas and Persian Gulf (following PSHA zonation). ~ 5 000 000 sources
- Assessment along the entire coast of the Arabian and Red Sea and Persian Gulf with high density of points-of-interest
- Two alternative probabilistic models.
- Calculated hazard strongly depends on model assumptions. More alternatives should be tested to fairly estimate uncertainties
- Constraints on focal mechanism are weak (few CMT observations in many zones): may considerably over-weight physically less realistic BS scenarios

Recommendations for the development of PTHA (Version 2.0) are

1) Make various views of the probabilistic dataset including site de-aggregation for the sides planned for inundation mapping
2) Compare to recent alternative models (Salah et al.'21, Zafarani et al.'22)
3) Need of more alternative seismic models to better explore uncertainty. First of all, M_{max} and rate models
4) Consider Splay faults for higher versions of PTHA. Recent studies (Momeni et al., 2022) show the importance of splay faulting.
5) Future development from area- to fault-based PTHA.

General recommendations and plans

1) One important result of the Abu Dhabi workshop is that INCOIS (India) is ready to host the PTHA database and to offer data and information following FAIR principles.
2) Another recommendation is that the inundation modeling for evacuation planning in the already defined pilot regions shall be done in 2023 using the results of PTHA (Version 1.0). It still has to be decided if the evacuation planing shall be based on a worst case scenario or a most probable scenario. This discussion has to be done between modellers and the respective decision makers.

Literature

Basili, R. et al. (2021). The Making of the NEAM Tsunami Hazard Model 2018 (NEAMTHM18). Frontiers in Earth Science, 8. doi: 10.3389/feart.2020.616594

Behrens, J. et al. (2021). Probabilistic Tsunami Hazard and Risk Analysis: A Review of Research Gaps. Frontiers in Earth Science, 9. doi: 10.3389/feart.2021.628772

Davies et al. (2017): A global probabilistic tsunami hazard assessment from earthquake sources. Geological Society, London, Special Publications, 456, https://doi.org/10.1144/SP456.5

Cummins, P. (2004). Small threat, but warning sounded for tsunami research. *AusGeo News, 75*, 4-7

El-Hussain et al. (2016): Probabilistic tsunami hazard assessment along Oman coast from submarine earthquakes in the Makran subduction zone. Arab J Geosci (2016) 9: 668 (doi: 10.1007/s12517-016-2687-0)

El-Hussain, I., Al-Shijbi, Y., Deif, A. et al. (2018): Developing a seismic source model for the Arabian Plate. Arab J Geosci 11, 435. https://doi.org/10.1007/s12517-018-3797-7

Giblin, J., Damlamian, H., Davies, G., Weber, R. & Wilson, K. (2022): Earthquake scenario selection for tsunami inundation hazard assessment: Guideline on using the 2018 Probabilistic Tsunami Hazard Assessment in the Pacific. Joint publication by the Pacific Community (SPC) and Geoscience Australia. Noumea, New Caledonia.

Grezio, A. et al. (2017). Probabilistic Tsunami Hazard Analysis: Multiple Sources and Global Applications. Reviews of Geophysics, 55(4), 1158-1198. doi: 10.1002/2017RG000579

Heidarzadeh & Kijko (2011): A probabilistic tsunami hazard assessment for the Makran subduction zone at the northwestern Indian Ocean. Nat Hazards 56:577–593 (doi: 10.1007/s11069-010-9574-x)

Hoechner et al. (2016): Probabilistic tsunami hazard assessment for the Makran region with focus on maximum magnitude assumption. Nat. Hazards Earth Syst. Sci., 16, 1339–1350 (doi: 10.5194/nhess-16-1339-2016)

Momeni, P., Goda, K., Mokthari, M. and Heidarzadeh, M. (2022): A new tsunami hazard assessment for eastern Makran subduction zone by considering splay faults and applying stochastic modeling. Coastal Engineerin Journal, https://doi.org/10.1080/21664250.2022.2117585

Rashidi et al. (2018). Tsunami hazard assessment in the Makran subduction zone. ArXiv:1803.11481v1 [physics.geo-ph] 30 Mar 2018

Salah, Sasaki & Soltanpour (2021): Comprehensive Probabilistic Tsunami Hazard Assessment in the Makran Subduction Zone. Pure Appl. Geophys. (https://doi.org/10.1007/s00024-021-02725-y)

Zafarani et al. (2022): Probabilistic tsunami hazard analysis for western Makran coasts, south-east Iran. Nat. Hazards (https://doi.org/10.1007/s11069-022-05595-2)