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Review Paper

Researching Tsunami Hazards in Makran: Insights into Challenges and Non-Seismic and Complex Source Tsunamis

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ABSTRACT

The Makran Subduction Zone (MSZ), located in the northwestern Indian Ocean, is a region with significant tsunami hazard potential due to its tectonic setting and history of seismic activity. While megathrust earthquakes have traditionally been regarded as the primary source of tsunamis in this region, recent research indicates that tsunamis may also be generated by a variety of other mechanisms. These include seismic events originating from local normal and splay faults, as well as non-seismic processes such as submarine landslides and meteorological phenomena, collectively referred to as "Non-Seismic and Complex Source Tsunamis." The recognition of these diverse tsunami-generating mechanisms has positioned the MSZ as a critical area of study, attracting considerable scientific attention over the past two decades. Researchers have focused on understanding the historical and paleotsunami records, identifying tsunamigenic sources, and advancing tsunami numerical modeling and hazard assessment techniques specific to the Makran region. This paper reviews the latest developments in tsunami research related to the MSZ, with a particular emphasis on Non-Seismic and Complex Source Tsunamis and the associated challenges in the accurate assessment of tsunami hazards in this tectonically complex region.

Keywords:
Makran; Tsunami; Numerical modeling; Hazard assessment; Complex sources; Challenges

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1. Introduction

The Makran Subduction Zone is the convergent plate boundary between the Arabian Oceanic Plate and the overlying Eurasian Plate. Subduction along this boundary occurs at a convergence rate of about 20 mm/yr. The MSZ is located offshore of Iran and Pakistan between the Strait of Hormuz and the Indus Plain, and has become an excellent natural laboratory for earth science studies. The Makran region has a very wide accretionary prism of 350-400 km and a very thick sediment section of up to 7 km. The MSZ appears to be segmented into western and eastern sections due to the pattern of offshore seismicity (Figure 1). The apparent difference in seismicity between the western and eastern Makran entails significant uncertainty regarding the tsunami hazard for the region. The seismicity of the MSZ is low compared to its adjacent seismic zones to the west and east; however, Makran is considered an active subduction zone that has produced tsunamigenic earthquakes (Mokhtari et al., 2008).

In the wake of the devastating 2004 Indian Ocean tsunami, the Makran Subduction Zone (MSZ) has attracted significant attention from the scientific community. This disaster stimulated scientists to research tsunamis and their impacts around the world, especially in the Indian Ocean. The MSZ is notable for its historical tsunamis, which has made it a focal point for research due to its intriguing tsunamigenic history and uncertain future. Over the past two decades, numerous studies have explored various aspects of tsunami research in this area, including tsunami history, potential sources, numerical modeling, hazard assessments, and paleotsunami investigations. This article aims to provide a concise overview of tsunami hazard research for the MSZ while addressing some of the challenges associated with evaluating tsunami risks in this region. A scientific study on the Makran tsunami hazard faces numerous uncertainties, primarily arising from the current and future am-biguity regarding the seismo/tsunamigenic potential of the MSZ. While it may produce tsunamis generated by landslides, the likelihood of a significant earthquake-induced tsunami remains unpredictable. Despite these challenges, recent advancements, particularly in paleotsunami research and the investigation of tsunamigenic structures and geometries, indicate a growing interest in this field. It is crucial to develop a more accurate understanding of the Makran tsunamigenic potential. Tsunamis are surprising, unpredictable, and often unexpected

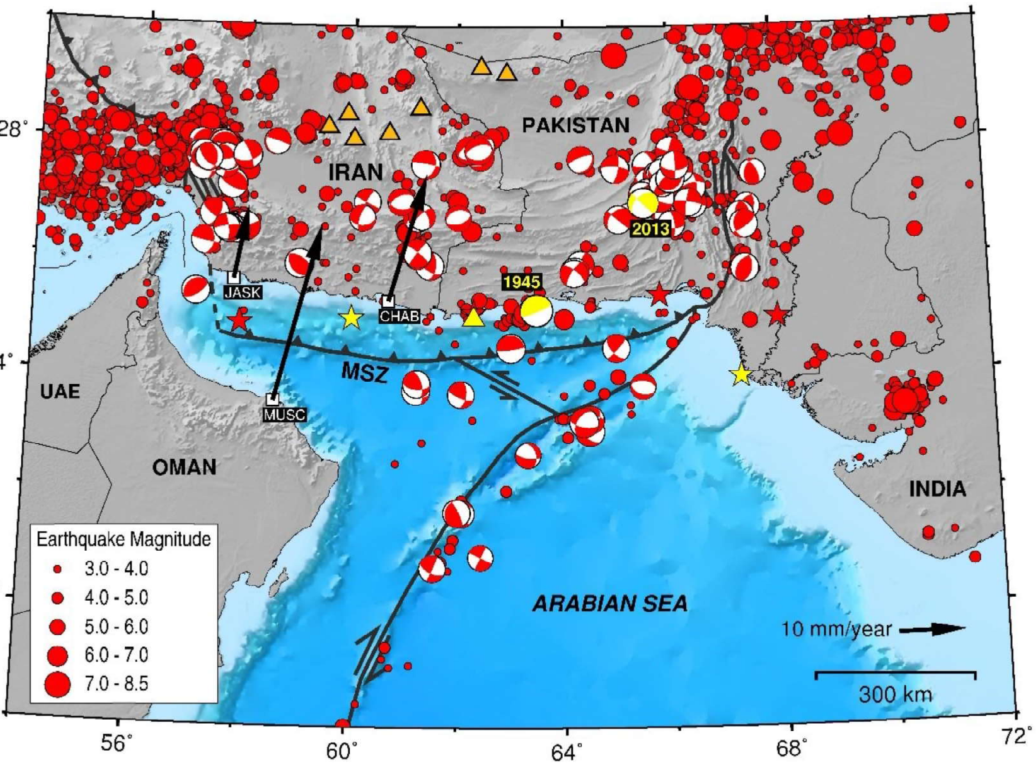


Figure 1. Seismicity of the Makran subduction zone (Rashidi et al., 2020a). Tsunami events are shown in yellow. Stars represent historical earthquakes. Orange and yellow triangles show volcanoes.

phenomena, demonstrating that any subduction zone in the world can be prone to such events. Given that the Makran has demonstrated its capacity to generate both seismic and non-seismic tsunamis, ongoing research in this area is essential (Rashidi et al., 2020a). In summary, it is vital to highlight these key points and recognize the significant studies conducted to date. Continued exploration of the Makran Subduction Zone will enhance our understanding of tsunami hazards and enlighten future preparedness efforts. This research is an extension of the previous work (Rashidi et al., 2024) previously presented at the 9th International Conference on Seismology and Earthquake Engineering, Tehran, Iran.

2. Tsunami Research in Makran

Tsunami-related studies of the Makran subduction zone are mostly focused on four main topics including: 1) tsunamigenic potential, 2) historical and modern tsunami history, 3) paleotsunami, and 4) numerical modeling of tsunami hazards. While the majority of tsunami studies focus on tsunami modeling, a significant gap remains in paleotsunami research, accounting for only 9% of Makran-related tsunami investigations (Figure 2). However, recent efforts, particularly in paleotsunami research, demonstrate a notable level of interest among researchers (Mokhtari et al., 2023).

Various studies have been undertaken to assess the tsunamigenic potential of the Makran region, including investigations into seismotectonics, geological evidence, geophysics, seismic reflection, thermal modeling, and tide gauge records. Multiple studies have emphasized the capability of the MSZ to generate tsunamigenic earthquakes. The MSZ segmentation and its thick sedimentary layers control the upper limit of earthquakes. The degree of interplate locking within the Makran subduction zone is closely linked to the consolidation of sedimentary layers (Pararas-Carayannis, 2006). Analysis of 2D seismic reflection data in the Makran region has investigated the relationship between key structural components and the megathrust, shedding light on its tsunamigenic potential. It has been proposed that the absence of a trench in the Makran may be attributed to the shallow dip of the subducting plate (Mokhtari et al., 2008). Similar marine terraces along the eastern and western shorelines of Makran suggest comparable tsunamigenic activity in these regions (Mokhtari et al., 2008). Thermal modeling results for the Makran region indicate a broad potential seismogenic zone within the MSZ, capable of producing tsunamigenic earthquakes with magnitudes ranging from Mw 8.7 to 9.2 (Smith et al., 2013). Analysis of modern and historical seismicity, coupled with sedimentary evidence, suggests a locked phase for the current state of the western Makran, indicating similar tectonic potential to the eastern Makran (Rajendran et al., 2013).

The MSZ has encountered two modern tsunamis in 1945 and 2013. Furthermore, the Makran subduction zone's tsunami catalog, provided by Heidarzadeh et al. (2008a), indicates the occurrence of at least four historical tsunamis in 326 BC, 1008, 1524, and 1897. Prizomwala et al. (2018) conducted a geological study along the Indian coastline, providing evidence for the 1008 tsunami. Their findings support the idea of significant historical earthquakes in the western Makran and do not dismiss other factors such as storms and meteotsunamis. Over the past decade, numerous researchers have conducted interviews and

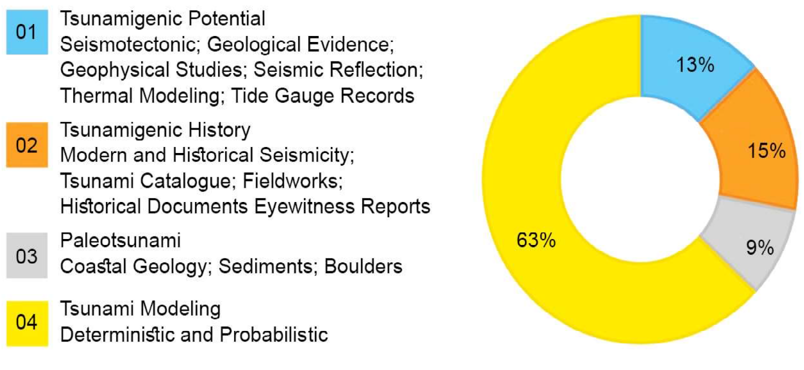


Figure 2. Statistics on the frequency of different types of tsunami studies for MSZ.

gathered various forms of information and historical reports to comprehend the impacts of the 1945 Makran tsunami. Hoffmann et al. (2013) collected eyewitness accounts, newspaper articles, and scientific reports to analyze the effects of the 1945 tsunami on the coastlines. They reassessed the death toll and concluded that the tsunami caused several hundred fatalities. Okal et al. (2015) reported the results of their field survey in 2010 along the Iranian coastline of Makran. Their fieldwork included interviewing tsunami survivors and measuring run-up heights at nine sites (ranging from 3 to 7 m). Lodhi et al. (2021) estimated the tsunami inundation parameters in Gwadar, Pasni, Ormara, and Karachi (Pakistan) using eyewitness accounts, newspaper reports, old maps, and field surveys.

Research in paleotsunami and coastal geology plays a crucial role in understanding the origins of extreme coastal deposits and reducing uncertainties about a region's tsunami history and future risk. For instance, Shah-Hosseini et al. (2011) conducted fieldwork and boulder transport modeling along the Iranian coast of Makran, providing evidence that a tsunami likely caused the coastal boulder deposits found there. Similarly, Hoffmann et al. (2015) identified tsunami-related deposits along the coast of Oman. More recently, a study by Hoffmann et al. (2020) introduced new sedimentological and archaeological evidence indicating the possible occurrence of a historical tsunami in the western Makran region about 1,000 years ago.

Various numerical modeling and hazard assessments have been conducted to comprehend the origins and consequences of tsunamis in the Makran Subduction Zone. Research on deterministic and probabilistic tsunami hazard studies in Makran has been examined, focusing on some of the valuable studies available. The 1945 tsunami in Makran has been the subject of multiple modeling and evaluation studies. Heidarzadeh et al. (2008b) compared their results on the 1945 tsunami with reported run-ups. Arjun et al. (2011) assessed the impact of the 1945 Makran tsunami run-up on the Indian southwest coast and the Lakshadweep Islands. Neetu et al. (2011) analyzed the significant waves of the 1945 tsunami through numerical modeling, suggesting that the high tsunami waves observed at Karachi result from tsunami wave energy being trapped on the Makran continental shelf. Several researchers have also simulated hypothetical tsunami scenarios in Makran. Okal and Synolakis (2008) estimated the tsunami hazard associated with ten megathrust scenarios in the Indian Ocean, including extreme scenarios for both the eastern Makran and the entire Makran subduction zone. Swapna and Srivastava (2014) highlighted the potential impact of the Murray Ridge on tsunami wave directivity, arrival time, and height. A study on social vulnerability in Gwadar, Pakistan, to earthquake and tsunami hazards underscores the urgent need to enhance social sustainability and implement effective risk mitigation and management strategies (Mengal et al., 2021).

Rashidi et al. (2018a) utilized slip models from actual tsunami events to create source models for the western Makran region, aiming to evaluate deterministic hazard in both near-field and far-field areas. Their findings suggested that a scenario similar to the 2015 Chile earthquake could be more applicable to the western Makran.

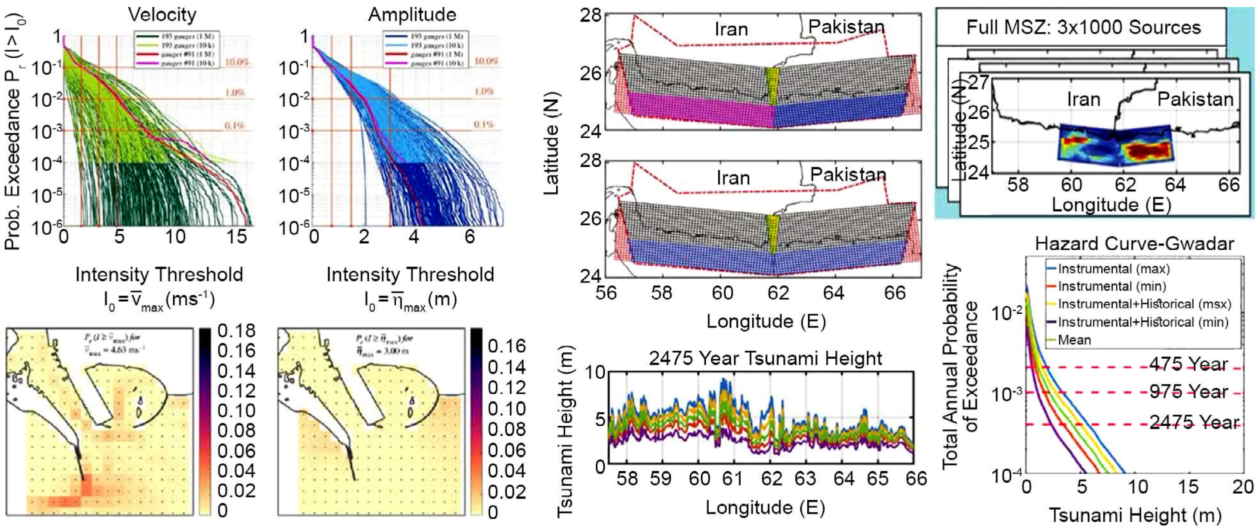
The variation in slip distribution and the location of the largest stress points (asperities) were found to have a significant impact on the potential for generating tsunamis. In a separate study, Rashidi et al. (2018b) analyzed how tsunami wave energy evolves over time and space in the Makran Subduction Zone (MSZ), focusing on the relationship between its potential and kinetic energy components. Their findings revealed that only a small fraction of the seismic energy is transferred into tsunami wave energy. Additionally, Rashidi et al. (2020b) modeled the effects of horizontal seabed displacements on tsunamis in the western Makran. Their analysis showed that these horizontal shifts led to a modest 4% increase in maximum tsunami wave amplitude and a 9% increase in tsunami wave energy.

In a pioneering investigation, Heidarzadeh and Kijko (2011) conducted a probabilistic tsunami hazard assessment (PTHA) for three Mw 8.1 sources in the Makran region. Hoechner et al. (2016) applied numerical simulations of earthquakes from a synthetic catalog to illustrate probabilistic tsunami hazard curves for the coastlines of Iran, Pakistan, and Oman. El-Hussain et al. (2016) developed a logic-tree approach to present a PTHA for Oman, considering various scenarios with different magnitudes in the MSZ. Gopinathan et al. (2021) utilized statistical emulation techniques to perform a probabilistic analysis of tsunami currents resulting from rupture scenarios in the Makran subduction zone (Figure 3a). Rashidi et al. (2020c) generated a series of random heterogeneous source models of the MSZ to assess the probabilities of tsunami hazards along the Makran shorelines. They presented hazard curves and probabilistic tsunami hazard maps for the coastlines. In a recent study by Salah et al. (2021), the probabilistic hazard of various small and large sources on a slab model of the MSZ was estimated. A more recent PTHA (Momeni and Goda, 2024) uses stochastic simulations of earthquakes with magnitudes between 7.7 and 9.1. Momeni and Goda (2024) examine uncertainties in earthquake occurrence rates, rupture scenarios, and slip heterogeneity, presenting results from 15,000 simulated models, including probabilistic tsunami height ranges for 475-, 975-, and 2475-year intervals (e.g., Figure 3b).

The latest study by Zafarani et al. (2023) conducted a comprehensive probabilistic tsunami analysis using a logic tree approach, incorporating multiple uncertainties such as maximum seismic magnitude, seismic coupling coefficient, and the presence or absence of splay fault slip distribution in probabilistic calculations for the western Makran region. In comparison to other studies, Zafarani et al. (2023) has thoroughly addressed the most probable uncertainties related to the MSZ, as well as earth subsidence effects for the first time. As a result, it stands out as a valuable current reference for comprehending the probabilistic tsunami hazard in the region. Another notable aspect of this research, in contrast to earlier works, is the introduction of the first tsunami hazard zonation for the coastal regions of western Makran and more especially consideration of the seismic coupling coefficient (e.g., Ghadimi et al., 2023). The study has generated various outputs, including hazard curves, earth subsidence plans, and uniform hazard maps. The outcomes of this probabilistic analysis are displayed in Figures (4) and (5).

3. Current State of Non-Seismic and Complex Source Tsunamis Research in Makran

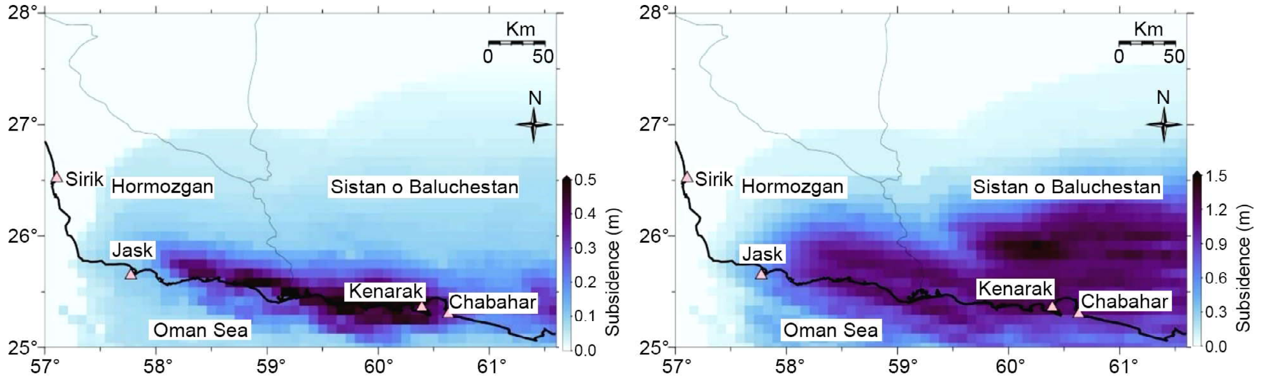
Traditionally, the primary focus of research on tsunami hazards in the Makran region has been centered on subducting scenarios. However, recent investigations have shed light on the significance of other sources that contribute to the intricate nature of tsunami hazards in this region. In Makran, complex seismic sources of tsunamis include normal faults, splay faults, and non-seismic sources. Splay faults are smaller subsidiary faults that branch out from a main fault. While they typically occur in conjunction with megathrust earthquakes, thereby amplifying tsunami risk, there are instances in which they can independently generate tsunamis. Splay faults in the MZS region



(a) Gopinathan et al. (2021)

(b) Momeni and Goda (2024)

Figure 3. Results of two example studies (a and b) on probabilistic tsunami modeling in Makran.



(a) (b)

Figure 4. Earth subsidence plans for the western Makran corresponding to return period of 475 (a) and 2475 (b) years modified after Zafarani et al. (2023).

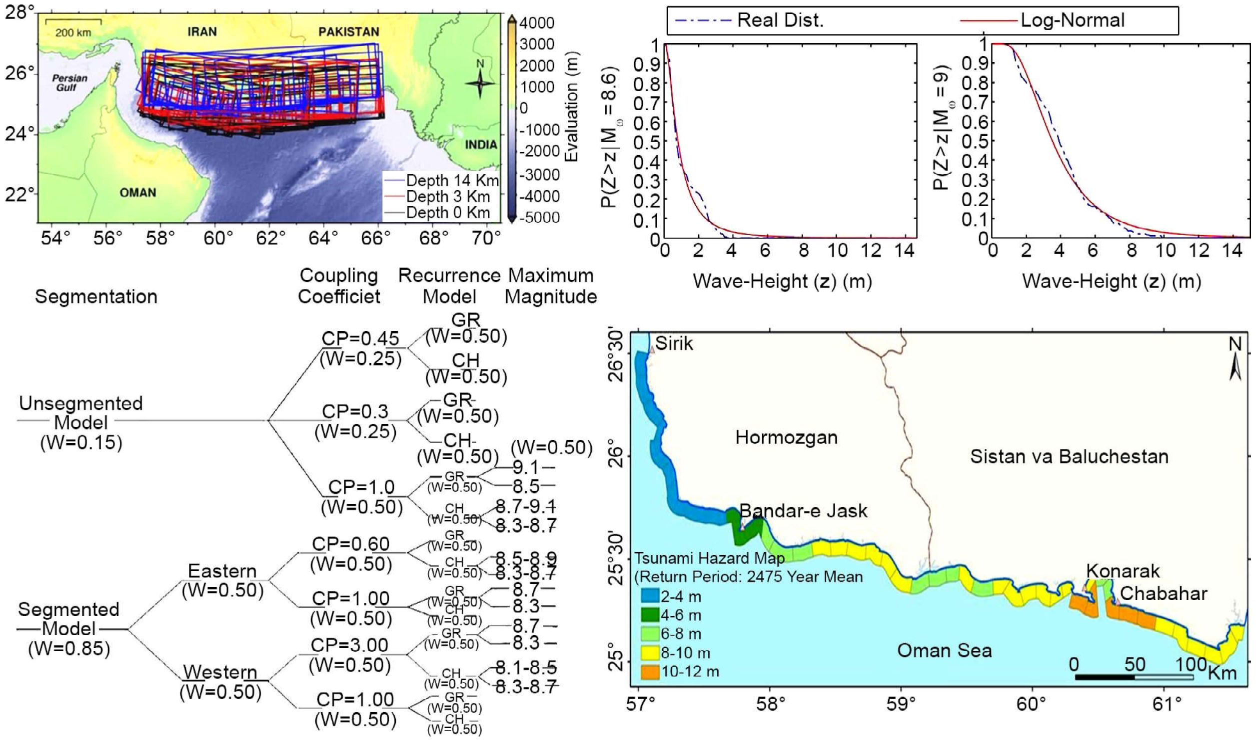
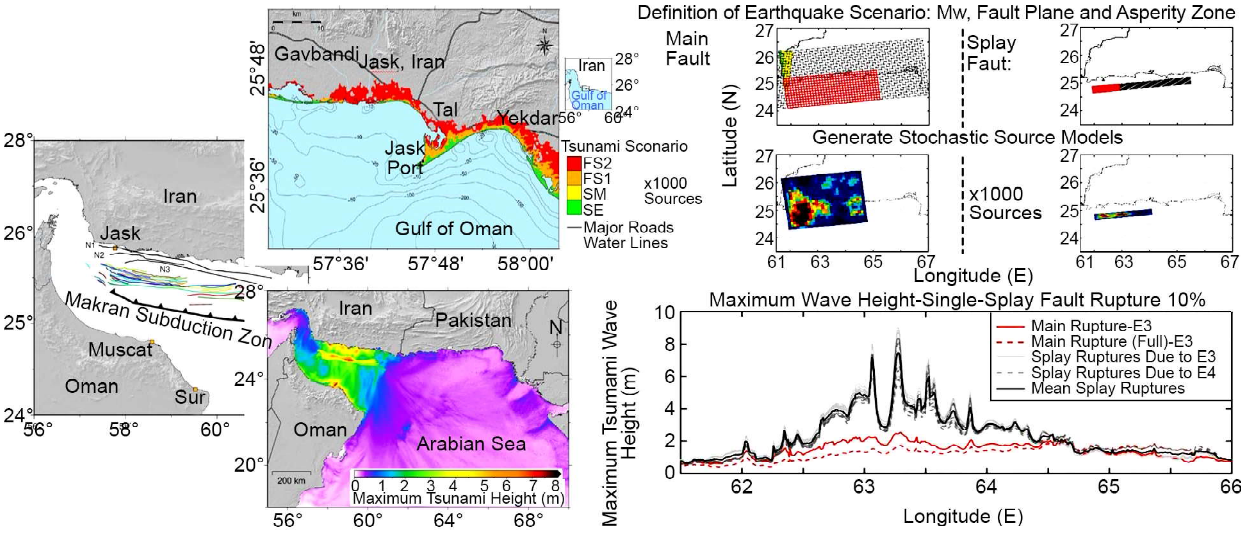


Figure 5. Results of probabilistic tsunami modeling by Zafarani et al. (2023 for MSZ).

are noteworthy geological features that play a vital role in shaping the offshore tectonics of the area. Previous studies have identified the presence of these faults along the MSZ (Mokhtari, 2015; Rashidi et al., 2022). Rashidi et al. (2022) examined the tsunami risks associated with both normal and splay faults in the western Makran region (Figure 6). They evaluated both deterministic and probabilistic tsunami hazards resulting from normal and splay faults in the MSZ region. Additionally, Momeni et al., (2023) simulated the potential tsunami hazard resulting from the rupture of stochastic splay fault models in the eastern Makran region (Figure 6).

While thrust earthquakes are commonly linked to tsunamis, it is crucial to recognize that normal faulting can also generate destructive tsunamis. There have been several instances worldwide where normal faults have triggered significant tsunamis. The Makran Subduction Zone (MSZ) is a region with complex geological features, as highlighted by numerous studies, including Mokhtari et al. (2008). Recent research by Pajang et al. (2021) indicates that active listric normal faults, which curve and flatten with depth, extend down to the megathrust along both the eastern and western coastlines of the MSZ. This finding further emphasizes the complex tectonic activity of the



(a) Rashidi et al. (2022)

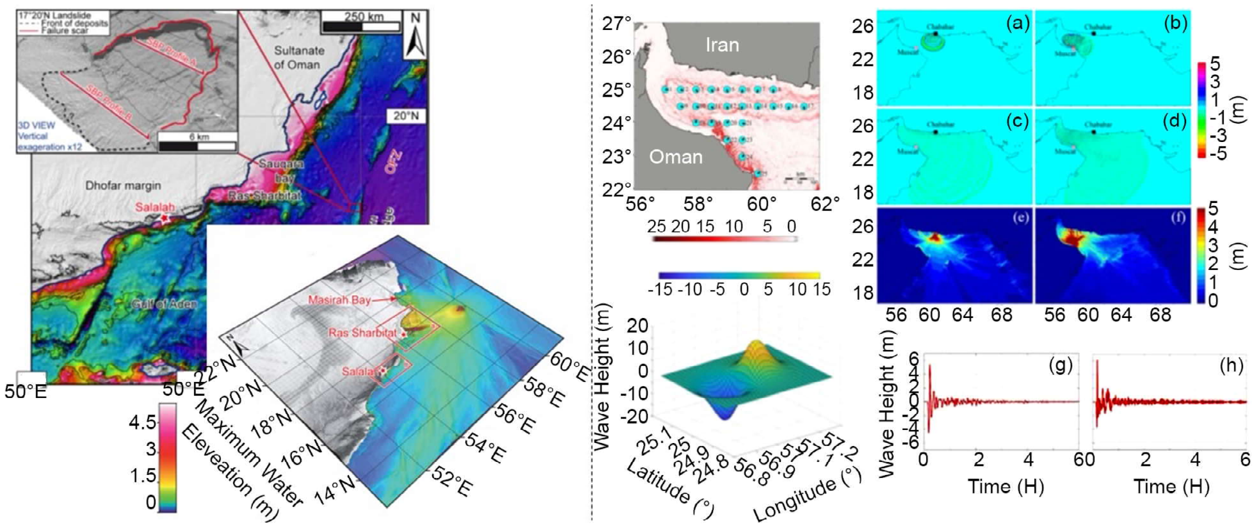
(b) Momeni et al. (2023)

Figure 6. Results of two example studies (A and B) on tsunami modeling of splay faults in Makran.

area. Given the potential for tsunamis generated by normal faults, it is recommended to integrate the assessment of these faults into regional tsunami hazard models. This approach would help to provide a more comprehensive understanding of tsunami risk, particularly in regions with complex fault systems like the MSZ. Additionally, more detailed geophysical surveys and modeling efforts should be conducted to map the extent and behavior of these listric normal faults, as their interaction with the megathrust could play a significant role in tsunami generation.

Unlike seismic tsunamis that are caused by underwater earthquakes, non-seismic tsunamis have different causes. In the MSZ, non-seismic tsunami sources can be categorized into submarine landslides and meteorological causes. Both the western and eastern sides of the MSZ have experienced submarine landslides and slumps in the past. Recent studies by Hoffmann et al. (2014) and Haider et al. (2023) suggest that some tsunamis in the MSZ may have been accompanied by submarine mass movements, despite limited historical records. Submarine landslides appear to be the second most significant source of tsunamis in the Makran region (Rashidi et al., 2020b). Any earthquake occurring nearshore or offshore in this area could trigger either submarine or subaerial tsunamigenic landslides. Heidarzadeh and Satake (2014) propose a landslide mechanism for the 2013 Makran tsunami, while Heidarzadeh and Satake (2017) demonstrate the significant role of a landslide in the 1945 tsunami in Makran. The sedimentary layers in the MSZ are characterized by low seismic velocities and high levels of trapped fluid, increasing the risk of sediment collapse and the triggering of large submarine landslides that can generate tsunamis. The combination of geological and tectonic factors in this region makes it particularly susceptible to such events. Deep-water submarine landslides, triggered by earthquakes from the active fault system of the Owen Fracture Zone, can potentially generate local tsunamis along the eastern coast of Oman (Rodriguez et al., 2013; Figure 7).

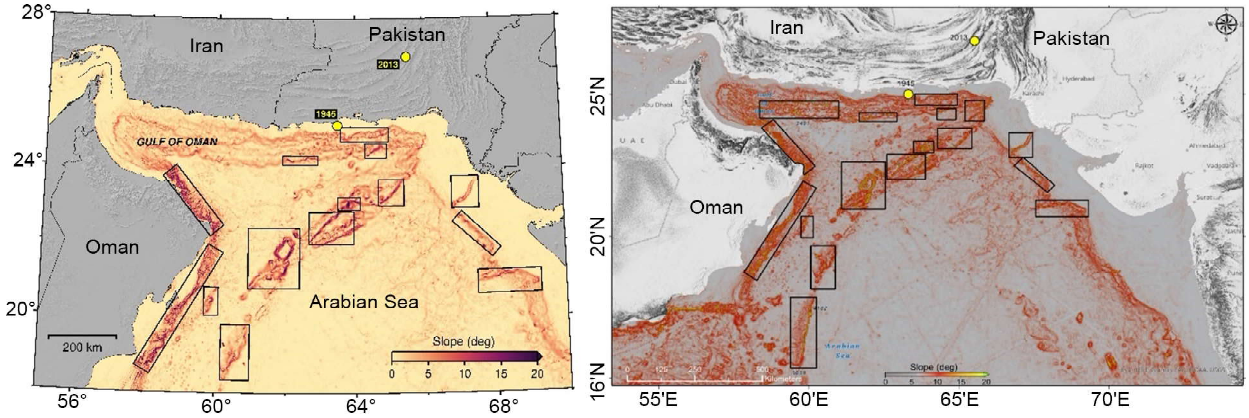
Salmanidou et al. (2019) utilized statistical emulation to generate 500,000 trial landslide tsunami scenarios in the Indus Canyon, NW Indian Ocean, and assessed their probabilistic tsunami hazard, assuming the landslide tsunami potential of the MSZ. Nouri et al. (2023) focused on modeling 100 submarine landslide-tsunamis occurring off the western Makran coast (Figure 7) in their research. The results of tsunami simulations indicate that Chabahar in Iran, and Muscat in Oman are particularly vulnerable to landslide-generated waves compared to other areas. A primary map created by Rashidi et al. (2020b) shows several locations in Makran that are vulnerable to potential submarine landslides (Figure 8). This map was subsequently updated by Gardezi et al. (2024) to include additional areas at risk (Figure 8).



(a) Rodriguez et al. (2013)

(b) Nouri et al. (2023)

Figure 7. Results of two example studies (A and B) on landslide tsunami modeling in Makran.



(a)

(b)

Figure 8. (a) Slope gradient map of the Makran bathymetry and locations of areas prone to submarine landslides (Rashidi et al., 2020b). (b) Same map was modified after Rashidi et al. (2020b) by Gardezi et al. (2024). Yellow circles show the locations of the 1945 and 2013 tsunamigenic earthquakes.

Meteorological tsunamis, or meteotsunamis, are tsunami-like sea waves resulting from strong atmospheric disturbances (e.g., Monserrat et al., 2006; Rabinovich, 2020). They occur due to sudden changes in atmospheric pressure, often associated with severe weather systems such as thunderstorms, squalls, or cyclones. Meteotsunamis have similar frequencies and destructive potential as regular tsunamis and can inflict significant damage to ports and coastal communities. Their occurrence is not confined to specific regions or countries, posing a global risk. In terms of coastal hazards such as tropical cyclones and meteotsunamis, the northwestern Indian Ocean remains relatively unexplored. There have been no reported instances of meteotsunamis in the Gulf of Oman; however, both the Gulf of Oman and the northwesterern Indian Ocean have experienced intense tropical cyclones. In the northwestern Indian Ocean, tropical cyclones typically form before or after the monsoon season (Haider et al., 2023). During cyclonic events, meteotsunami waves could potentially be generated. The onshore stratigraphic record of the northwestern Indian Ocean, as studied by Hoffmann et al. (2015), offers valuable evidence of past extreme wave events. Recent studies indicate a global risk associated with meteotsunamis, as they can manifest in any coastal area, yet documented instances in offshore Makran remain scarce. Nevertheless, the Persian Gulf, adjacent to the Gulf of Oman, has shown potential for this phenomenon. A notable meteotsunami occurred on March 19, 2017, resulting in a maximum run-up of about 3 m (Heidarzadeh et al., 2020).

The 1897 tsunami in Makran is suggested to have a meteorological origin (i.e., ocean storms), while Heidarzadeh et al. (2008a) proposed a volcanic mechanism, citing reports of dead fish at the time. It is also important to acknowledge that meteotsunamis can arise from tropical cyclones (Shi et al., 2020). Although no empirical evidence supports the existence of meteorological tsunamis in the Gulf of Oman, powerful tropical cyclones have been reported in the region (e.g., Fritz et al., 2010), indicating possible meteotsunamigenic potential.

4. Challenges in Tsunami Hazard Assessment for Makran

4.1. Tsunami Generation

Conducting a comprehensive tsunami hazard assessment for the Makran subduction zone is quite difficult, whether using deterministic or probabilistic methods. The most significant challenge lies in evaluating the current tsunamigenic potential of the MSZ, particularly in its western segment. Due to a lack of recent tsunamigenic seismicity and insufficient geophysical and geological data, it remains unproven whether the western Makran is currently locked. Nevertheless, historical tsunami events and the landslide-generated tsunami of 2013 indicate that the region is susceptible to both seismic and non-seismic tsunamis.

These uncertainties pose challenges in defining tsunami scenarios for numerical modeling and hazard analyses. The lack of comprehensive, high-resolution seismic data, marine GPS stations, and seafloor sensors restricts our understanding of fault geometry in the region. Even if the zone is indeed locked, it remains unclear whether it is partially or fully locked (Byrne et al., 1992; Hoffmann et al., 2020), as well as the magnitude and extent of locking between the two tectonic plates. Detailed seismic coupling maps for the MSZ are still unavailable. The trench's location is also uncertain, given that the down-going plate has a very shallow dip (~ 2-3°) and is covered by thick sedimentary layers. The seismogenic depth of the subduction zone is ambiguous due to insufficient seismic data. For these reasons, most tsunami modelers tend to utilize hypothetical planar fault planes for Makran, though some studies have explored non-planar geometries for the subduction interface (e.g., Hoechner et al., 2016; Rashidi et al., 2020c). Recently, tsunami researchers have utilized the Slab2 model (Hayes et al., 2018), which provides 3D geometries of all active subduction zones, in several studies related to Makran (e.g., Momeni et al., 2020; Gopinathan et al., 2021; Salah et al., 2021).

Most studies assume a uniform slip distribution for rupture models, which is the common approach in conventional tsunami modeling, but it may lack precision. Variability in slip can significantly affect near-field tsunami wave amplitudes and run-up. Some researchers, however, have developed non-uniform slip models for the Makran subduction zone (e.g., Rashidi et al., 2018a, 2020c; Salah et al., 2021; Momeni et al., 2023; Zafarani et al., 2023; Momeni and Goda, 2024).

Although there is no clearly defined slip model for the 1945 Makran tsunami, Momeni et al. (2020) proposed a heterogeneous stochastic source model based on comparisons between simulated and observed tsunami wave time series across various stochastic models. Alternative approaches to incorporate slip heterogeneity into tsunami generation modeling include:

- Random slip models (e.g., Hoechner et al., 2016; Rashidi et al., 2020c, 2020a; Salah et al., 2021; Momeni et al., 2023; Zafarani et al., 2023),
- Non-uniform slip functions (e.g., Salmanidou et al., 2019),
- Scaled slip distributions from other tsunamigenic events (e.g., Rashidi et al., 2018a).

While most research has focused on megathrust tsunamis, the contribution of other tsunamigenic mechanisms, such as splay faulting and landslides, has not been adequately explored (Rashidi et al., 2024). These mechanisms can independently generate tsunamis or be triggered by megathrust events, thereby amplifying the initial tsunami hazards.

A study by Salmanidou et al. (2019) offers a probabilistic analysis of landslide-generated tsunamis, albeit limited to the eastern edge of the Makran subduction zone. Similar assessments for offshore areas of Pakistan, Iran, and Oman could hypothetically illuminate the potential hazards associated with future landslides. Tsunami modeling for landslides presents its own challenges due to uncertainties stemming from the unpredictable nature of landslide dynamics and locations, coupled with a scarcity of data, particularly in the data-sedicient Makran region. A specific challenge is accurately estimating the temporal evolution of a landslide from its initial position and integrating it into tsunami models.

As noted by Grezio et al. (2017), real data on the temporal dynamics of landslides are lacking, complicating the characterization of source parameters and tsunamigenesis. To simplify this complex issue, a static approach is sometimes adopted to model the initial sea surface deformation caused by the landslide, disregarding the dynamic aspects of the movement. This is typically achieved using empirical or analytical formulas to approximate the 3D shape of the initial wave, which can then be used as initial conditions for tsunami propagation modeling (e.g., Heidarzadeh & Satake, 2014; Salmanidou et al., 2019).

4.2. Sedimentation

Another factor contributing to uncertainty in tsunamigenic hazards in the Makran region may be the presence of thick sedimentary layers (Rashidi et al., 2018a). However, understanding the behavior of these sediments during a rupture is challenging. Sediments can exhibit different behaviors based on their level of consolidation, acting either as a fluid or as a viscoelastic solid.

Static models fail to account for sediment effects, necessitating the computation of the elastodynamic response of the seabed due to faulting. Dutykh and Dias (2010) explored how sedimentation influences seabed deformation. Their research indicated that sediments have minimal impact on seabed deformation when using a static approach. On the contrary, sediments can amplify vertical seabed displacements in dynamic solutions. They introduced a sediment amplification factor, defined as the ratio of maximum seabed uplift from a homogeneous model (Okada solution) to that from an inhomogeneous model (sedimentary layering). This effect is illustrated by a curve showing the sediment amplification factor (S_a) as a function of a dimensionless parameter known as relative depth (h_s/d), where h_s is the sediment layer thickness and d is the fault depth (Figure Dutykh and Dias, 2010; Rashidi et al., 2023). Gopinathan et al. (2021) utilized this curve to factor in sediment amplification in tsunami modeling for scenarios in the MSZ. Additionally, sediments may become mobilized during earthquakes and generate landslide-induced tsunamis, indicating that submarine slope stability analysis and geological field studies are essential in the Makran region to identify high-risk locations.

Beyond segmentation, thick sedimentary layers may also influence the upper limit of earthquakes in Makran. Pararas-Carayannis (2006) emphasized that the degree of sediment consolidation is crucial for interplate locking within the Makran subduction zone.

4.3. Seismicity

Estimating the annual rates of tsunamigenic earthquakes is vital for seismic-based probabilistic tsunami hazard assessments, typically accomplished using the Gutenberg-Richter magnitude-frequency relationship. Accurately defining the boundaries of the Makran subduction zone (seismic zonation) or its western and eastern segments is crucial, as it can create uncertainties in obtaining the magnitude-frequency relation for either segment or the entire subduction zone. Such zonation is generally performed by experts based on the seismotectonic characteristics of the area and is influenced by the available data and expert judgments (Grezio et al., 2017).

The seismicity parameter b in the magnitude-frequency relationship, along with the assumed maximum magnitude, significantly influences Probabilistic Tsunami Hazard Assessment (PTHA) outcomes. These factors introduce considerable uncertainty in the Makran region due to the limited availability of seismicity data.

The seismic segmentation of the Makran subduction zone into western and eastern parts has significant implications for assessing tsunami hazards, particularly in determining maximum magnitude and rupture length (Grezio et al., 2017).

4.4. Tsunami Numerical Modeling

A key issue highlighted in many numerical tsunami studies is the lack of high-resolution bathymetric data for the Makran coast, which can adversely affect the accuracy of results-particularly for nearshore and run-up/inundation estimates. Nonetheless, some studies have incorporated limited higher-resolution digital elevation models (e.g., Heidarzadeh and Satake, 2014; Payande et al., 2015; El-Hussain et al., 2018).

Another challenge in numerical simulations is the scarcity of historical data for validating results. The type of hydrodynamic equations used in tsunami propagation modeling can significantly influence the outcomes, depending on the scales of the computational domain, the tsunami source, and the source's relative location. Given that the western Makran is situated between the coastlines of Iran and Oman, a more judicious choice would be to employ nonlinear water wave equations.

Factors impacting tsunami run-up and inland inundation include coastal structures, the distribution of nearshore and coastal roughness, breakwaters, and vegetation. Ignoring these effects can lead to overestimations of run-up and inundation distances. Including these variables in numerical simulations for Makran coastlines presents challenges due to limited data availability in the region. As a precautionary measure, considering the effect of bottom friction in tsunami hazard assessments would be a safer and more conservative approach.

5. Conclusions

In continuation of our previous research (Rashidi et al., 2024), which was presented at the 9th International Conference on Seismology and Earthquake Engineering in Tehran, Iran, we have summarized the recent advancements in tsunami research related to the Makran region. Our focus is on the complexities of tsunamis and the challenges associated with tsunami hazard assessment in Makran. We emphasize that for effective utilization of tsunami hazard studies, there is a critical need for exceptionally precise, site-specific bathymetric data, particularly for inundation analyses. Moving forward, it is vital to focus more on several key paths of research, including more investigation of paleotsunami events, detailed examinations of coastal geology and the analysis of extreme-wave deposits. Additionally, comprehensive vulnerability assessments are essential for all Makran coastlines to better understand and mitigate potential risks. Furthermore, there is a pressing need to evaluate the hazard potential posed by complex tsunamigenic sources within the region. While megathrust tsunamis need specific large-scale seismotectonic conditions, non-seismic tsunamis in general can occur in almost every region and cause significant local damage.

One of the most pressing challenges in the field of seismology and tsunami research is the accurate assessment of the current tsunamigenic potential of the MSZ, with a particular focus on its western segment. It is essential to consider the implications of these assessments for coastal communities and infrastructure, as well as for developing disaster preparedness strategies. Additionally, the seismic segmentation of the Makran subduction zone directly affects tsunami hazard assessments. The role of sediments in tsunami generation remains insufficiently studied, and accurately modeling their behavior during a rupture poses significant challenges. Many researchers tend to use a uniform slip distribution in their tsunami models, which may lead to inaccuracies.

The assumptions identified reveal critical gaps and limitations in our current understanding and methods for assessing tsunami hazards in the Makran region. Each assumption highlights inherent uncertainties due to inadequate data, variations in modeling approaches, and a lack of research on sediment dynamics, subudction gemometry and seismic activity.

Together, these assumptions illustrate the complexities involved in developing reliable tsunami hazard assessments and underscore the necessity for enhanced data collection and modeling techniques to improve predictions of potential tsunami risks in the area.

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