A CASE-STUDY OF RUBBLE-MOUND BREAKWATERS STABILITY AGAINST MAKRAN SUBDUCTION ZONE TSUNAMIS

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A case-study pertaining to a number of existing breakwaters located on northern coastlines of the Gulf of Oman, directly facing the Makran Subduction Zone (MSZ) sets the context in order to elucidate the adopted methodologies for both Probabilistic Tsunamis Hazard Analysis (PTHA) as well as investigating breakwater stability in the event of a major tsunami. MSZ stretches from west to east for over *900* (*km*), affecting the coastlines of Iran, Pakistan, India, Oman and UAE as a potential source of tsunami hazard. According to historical data, the last reported MSZ generated tsunami which was triggered by the *1945*CE earthquake of *8.1* (Mw) magnitude caused human fatality figures of up to almost *4,000,* in addition to major structural devastation in its wake. Of particular interest, is the fate of existing breakwaters along the northern shorelines of the Gulf of Oman whose design criteria did not initially incorporate tsunami-related considerations, providing impetus for the modeling, design & analysis efforts presented in this article to serve the two-fold objective of assessing the need for strengthening existing structures, which are virtually all of the rubble-mound type, as well as deriving suitable design criteria for new breakwaters in the MSZ related tsunami affected region of Iran, earmarked for significant new developments.

Keywords: Makran Subduction Zone; Tsunami; Rubble-Mound Breakwater

INTRODUCTION

Makran Subduction Zone (MSZ) is an important natural hazard to consider for adopting a sound regional development approach concerning all its affected coastal zones, including more than 600 (km) of Iranian coastlines north of the Gulf of Oman. As a well-known tsunami-genic subduction zone situated about 100 (km) south of the Iranian coastlines, MSZ has been responsible for the catastrophic tsunami triggering earthquake in 1945CE.

As evident from the next page (Figure 1), MSZ extends for more than 900 (km) starting westward approximately from the mouth of the strait of Hormuz all the way to the east up to a location directly facing the Karachi city in Pakistan with the latter's more than 25 million inhabitants being just one of the existing and planned urban areas of concern.

Despite recent major interest by the international community to address the tsunami risks for this area, as for instance recently reported by Penney *et al.* (2017), there remains a need for more research on MSZ properties, however, it is often assumed that if the western part of MSD (in Iran) also produces earthquakes like it has been clearly the case for the eastern part – and the whole Makran megathrust would go on to move in one go – it may indeed potentially produce a magnitude 9 earthquake, similar to those in Sumatra and Tohoku with the calamitous aftermath of the resulting tsunamis in 2004 and 2011 CE, which were notably also generated by a subduction zone related mega-thrust.

Employing a network of 27 Global Positioning Stations (GPS) through a concerted bilateral effort by Iran and Oman to characterize MSD has revealed a fairly gentle subduction rate of around 19.5 (mm/yr), as reported by Heidarzadeh *et al.* (2004). However, more recent results such as by Smith *et al.* (2013) based on thermal modeling of MSZ, have suggested that earlier assumptions may have led to an underestimation regarding the possible earthquake magnitudes at MSZ; not ruling out extreme earthquake sizes of up to 9.2 (Mw), deeming MSZ a major hazard for its affected nearby countries in the Gulf of Oman and the Arabian Sea.

Within the above-mentioned context, thorough considerations are required in design of coastal structures such as dikes and breakwaters, in order to either ensure proper performance of such hard measures of tsunami risk mitigation, or to investigate their other intended function to protect harbors dedicated to commercial, fishery or multi-purpose ports, usually nearby densely populated coastal communities at this northern coastal region of the Gulf of Oman, which is also subject to regular swells arriving from the south-easterly sector during the Monsoon season as well as sporadic tropical cyclones. It deserves mention that no breakwaters have been constructed to-date in order to serve solely as tsunami barriers; however rapid urbanization and prioritized national development plans for this

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region may indeed necessitate such measures in the future based on merits of the social and/or economic value attributed to such future developments.

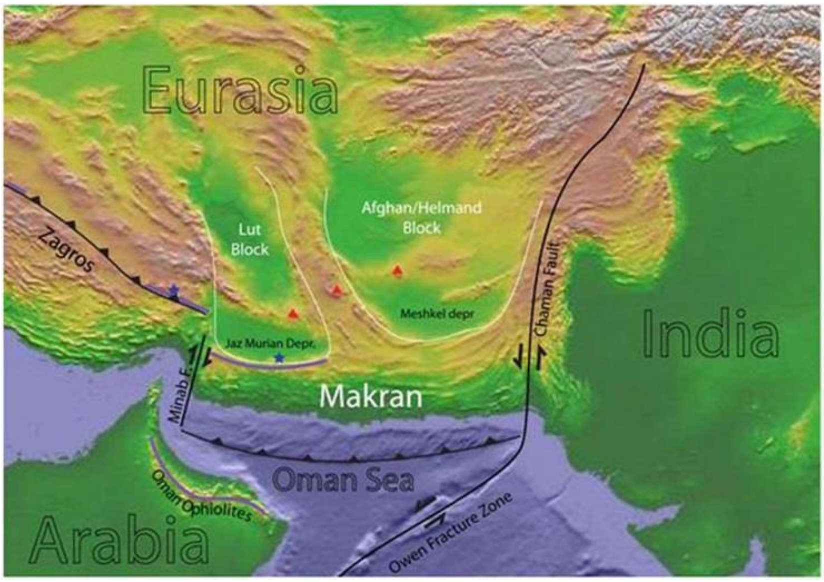

Figure 1. Tusnami-genic Makran Subduction Zone (MSZ) expanse opposite populated coastal communities.

For the purpose of the present manuscript, an account is presented of the anticipated tsunami events and their associated impact on six existing Iranian ports breakwaters, namely Jask, Karati, Zar-Abad, Konarak, Shahid Beheshti, and Pasa-Bandar, with their approximate locations being as depicted below (Figure 2). Regarding the design basis of the selected breakwaters, all are either conventional rubble-mounds or of the berm breakwater type. The above-mentioned selected ports at different locations along the northern coastlines of the Gulf of Oman are of particular interest also because Shahid Beheshti Multi-purpose port and Jask Commercial port are vital local hubs to import, export and transit of cargo, while Konarak, Pasa-Bandar and Zar-Abad are major industrial fishery ports in the area with Karati port being a multi-purpose port serving as a gateway for the adjacent coastal community consisting of a few nearby villages.

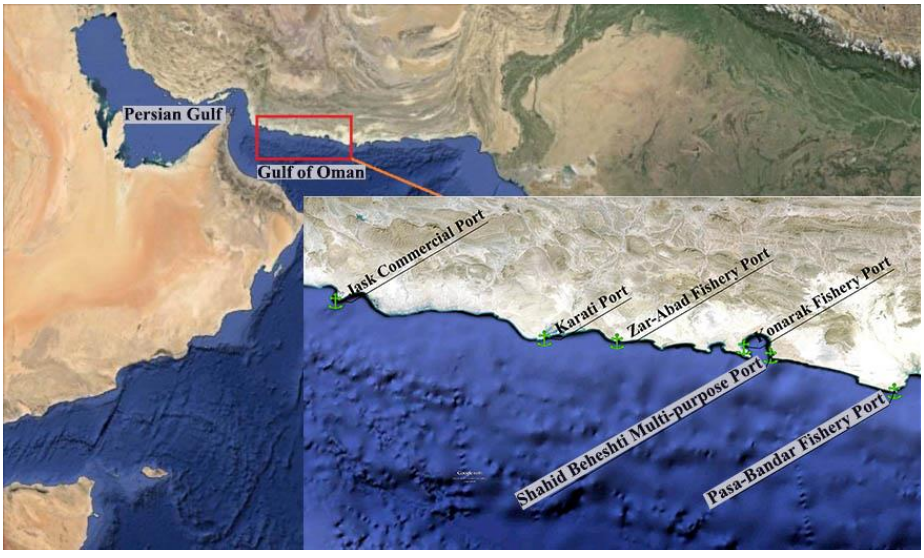

Figure 2. Names and locations of selected port breakwaters as constructed along northern Gulf of Oman coasts.

For the sake of performance assessment in case of tsunami impact, a summary of the treated breakwater types and their associated armoring information is provided, as stated below (Table 1):

Table 1. Summary of Selected Breakwaters Armor Units Properties

Breakwater	Type of Armor	Weight Range (ton)
Jask	Berm Stone	*2.5-7*
Karati	Berm Stone	*1.5-8*
Zar-Abad	Berm stone	*3-7.5*
Konarak	Conventional stone	*1-4*
Shahid Beheshti	Berm stone	*8-25*
Pasa-Bandar	2 Rows of Antifer blocks	*6*

It deserves mention that a pitfall of the present study is the relative lack of reliable data on MSZ properties, usable for this sparsely populated region of northern Gulf of Oman coasts –whose relative harsh environment and barrenness are reported by historians to have played a role in the demise of the army of Alexander the Great-, with no useable information existing on the actual distribution of tsunami wave-heights at the region regarding the 1945 event.

Presently, as the region is earmarked to become a focus of rapid urbanization and industrialization on both the Iranian and Omani sides, leading to more impetus on more in-depth international studies of MSZ, it is envisaged that more reliable tsunami source related data will become available in the near future.

PROBABILISTIC FORECAST OF SEISMIC HAZARD

In the face of significant uncertainties to properly define the seismological characteristics of MSZ, with the *1945* CE tsunami remaining the sole recorded tsunami event in living memory, the results of Heidarzadeh *et al*. (2011) are herein-forth followed, who estimated the Probability of MSZ earthquakes of varying magnitudes over the for the next 1, 50, 100 & 1000 years, as shown below (Figure 3):

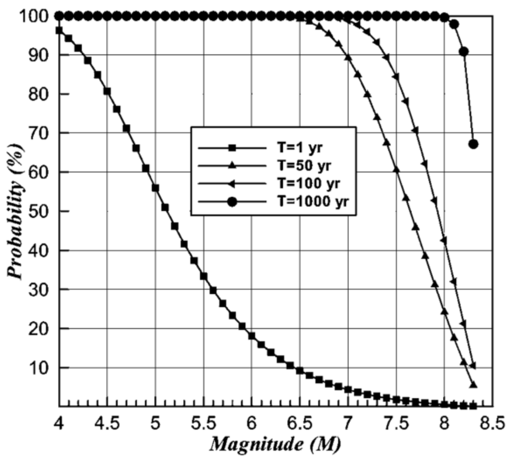

Figure 3. Probability of earthquakes of various magnitudes within the next 1, 50, 100 and 1,000 years.

For instance, the probability attributable to a 7.5 (Mw) earthquake over the next 50 years amounts to about 60%.

NUMERICAL MODELING OF TSUNAMI GENERATION AT SOURCE AREA

In the present study, it is strived to use the Probabilistic Tsunami Hazard Analysis (PTHA) approach according to Rikitake & Aida (1988), so as to associate a set of probabilities to MSZ tsunami wave-heights impacting each site of interest, considering the next 50 and 100 years.

Despite existing uncertainties, it is necessary to explore various earthquake scenarios having different magnitudes and locations. In this vein, the entire MSZ was divided into three tsunami generating sub-zones consisting of the eastern, central and western Makran, with the magnitudes of tsunami-genic earthquakes being assumed to vary from 7.5 to 9 (Mw) for all three above-mentioned sub-zones. Subsequently, a total of 18 scenarios were defined for the sake of simulating resulting tsunamis, as summarized in the following (Table 2):

Table 2. Scenarios for tsunami generation modeling at the Makran region.

Scenario No.	Size (Mw)	MSZ Seismogenic Sub-Zones		
		Western Makran	Middle Makran	Eastern Makran
1	*9*	■		
2	*9*		■	
3	*9*			■
4	*8.8*	■		
5	*8.8*		■	
6	*8.8*			■
7	*8.5*	■		
8	*8.5*		■	
9	*8.5*			■
10	*8.3*	■		
11	*8.3*		■	
12	*8.3*			■
13	*8*	■		
14	*8*		■	
15	*8*			■
16	*7.5*	■		
17	*7.5*		■	
18	*7.5*			■

In order to simulate the propagation of the tsunami waves associated with the above-mentioned scenarios, the well-known Community Model Interface for Tsunami (ComMIT) software has been employed for tsunami generation and propagation based on the Method of Splitting Tsunami (MOST) numerical model of 2D Nonlinear Shallow Water (NSW) equations, utilizing the finite-differences method of Titov and Gonzales (1997).

As customary in tsunami modeling, each simulation scenario consists in part of three separate phases, as follows: Firstly, tsunami generation with the initial tsunami wave-form being determined assuming the free surface water-level disturbance being equal to sea-bed deformation. Secondly, the propagation of tsunami wave from deep-water to shoreline is simulated prior to the last and third phase of run-up, and inundation of land to characterize the impact on coastal areas and facilities.

To serve the objective of increased modeling accuracy, a three-level nested grid approach (Figure 4) is adopted for solving the governing NSW equations, where the grid resolution gradually increases while moving from deep water towards the coastal areas of interest. According to each specific ports location, the definition of grid C varies in different simulations, while Grids A and B configuration remain the same.

As for model set-up data, the topographic data required for Grid C were extracted from 3 arc-second (~90 meters resolution) processed data-set of the Shuttle Radar Topography Mission (SRTM), courtesy of the U.S. National Aeronautics and Space Administration (NASA), while the bathymetry data was obtained from 30 arc-second grid of the General Bathymetric Chart of the Oceans (GEBCO) upon interpolation to 3 arc-second for integration with topographic data.

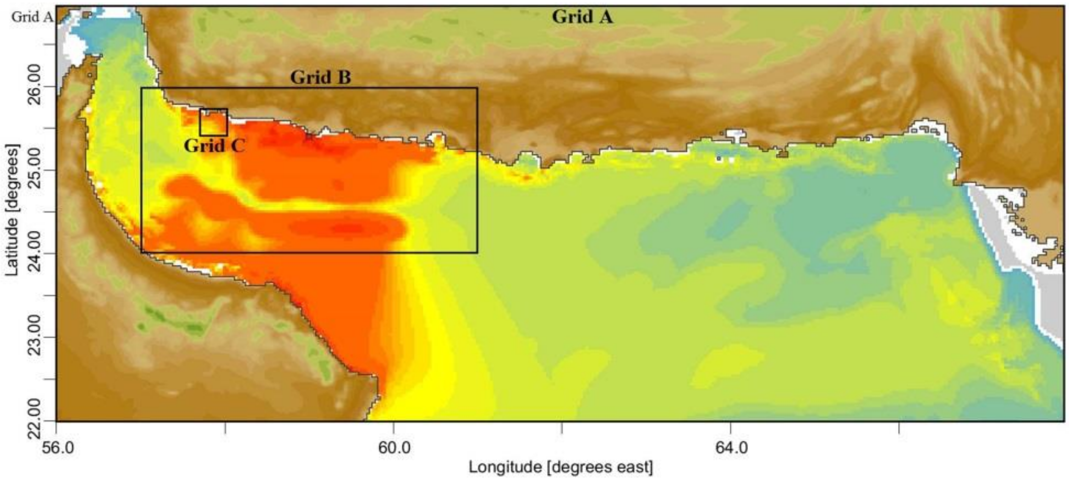

Figure 4. Nested grids sizes pertaining to Jask breakwater zone.

NUMERICAL RESULTS OF TSUNAMI WAVE PROPOGATION TO BREAKWATERS

Following figures demonstrate snapshots of free-surface displacements, at times: t=0, 15, 30 and 45 minutes, pertaining to scenario No.7, where Grid C has been focused on surrounding area of Jask breakwaters, with the tsunami waves arriving at Jask shores in less than 30 minutes after the earthquake occurrence.

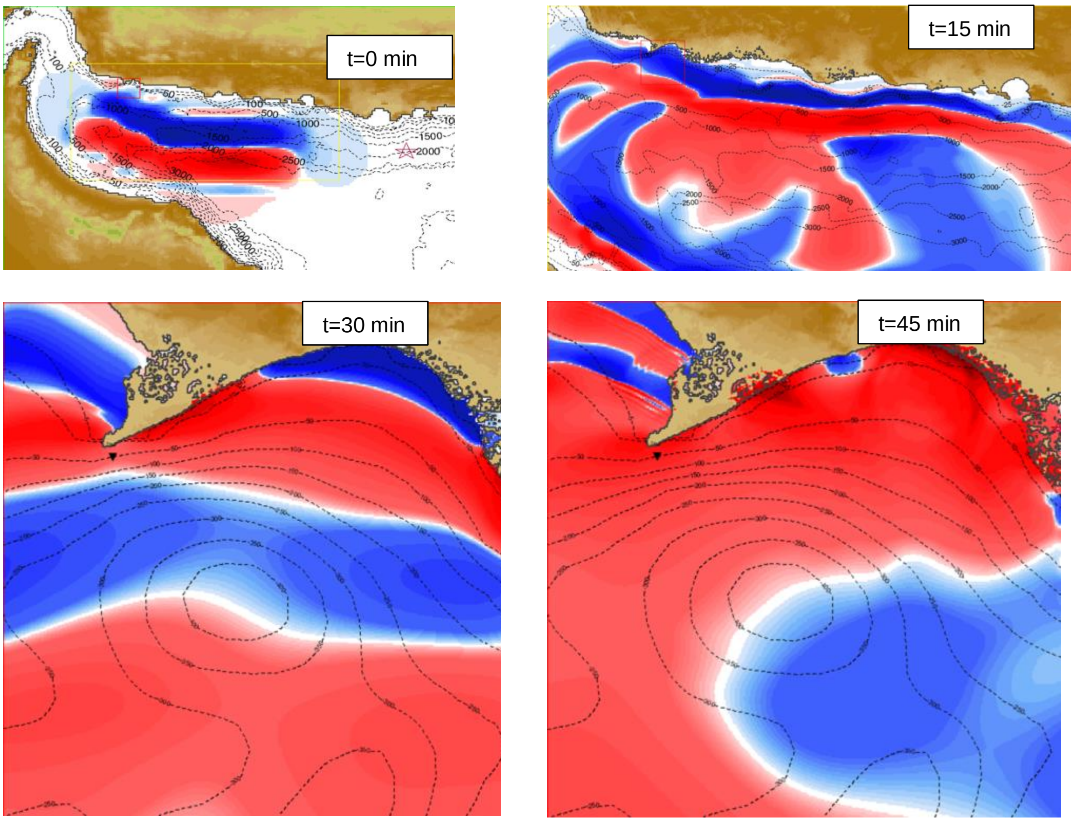

Figure 5. Snapshots of tsunami simulation results at times t=0, 15, 30 and 45 minutes for scenario No.7 (Grid C: Jask zone).

To obtain design tsunami wave-heights, time series of the arriving tsunami waves are extracted at some numerical stations within grid C in the vicinity of each of the breakwaters. Figures 8 to 13 illustrate the time series of wave-heights extracted corresponding to the afore-mentioned scenario No.2, *i.e.* the occurrence of a 9 (Mw) earthquake at central part of Makran.

In relative terms, the results imply that simulated wave-heights at breakwaters of Karati and Zar-Abad are much larger than at other locations, due to being directly impacted by tsunami waves, while some other locations are somewhat sheltered behind a headland, receiving diffracted tsunami waves.

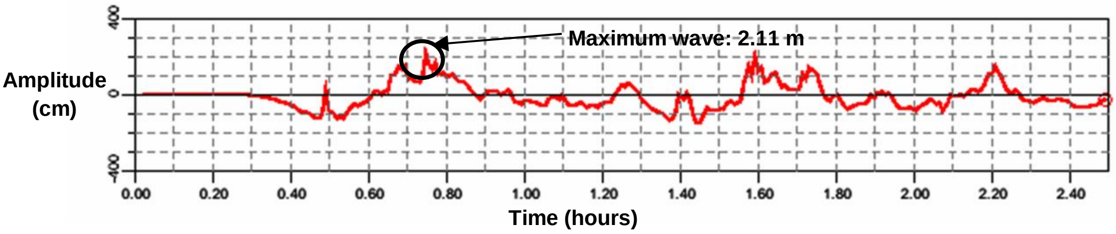

Figure 6. Maximum wave-height arriving at Beheshti breakwater.

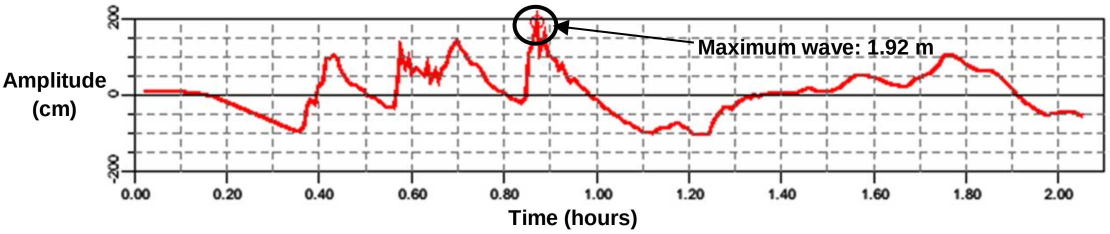

Figure 7. Maximum wave-height arriving at Jask breakwater.

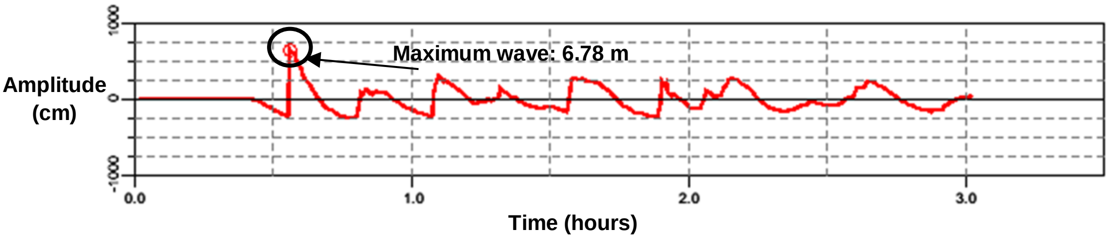

Figure 8. Maximum wave-height arriving at Karati breakwater

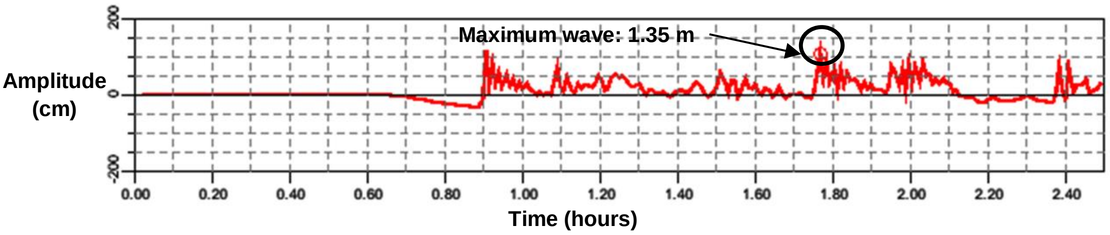

Figure 9. Maximum wave-height arriving at Konarak breakwater.

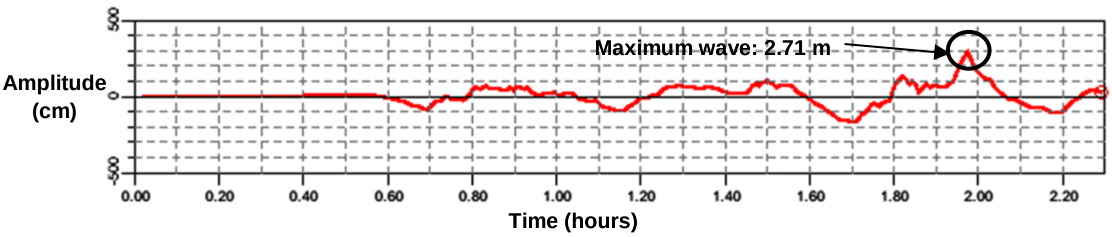

Figure 10. Maximum wave-height arriving at Pasa-Bandar breakwater.

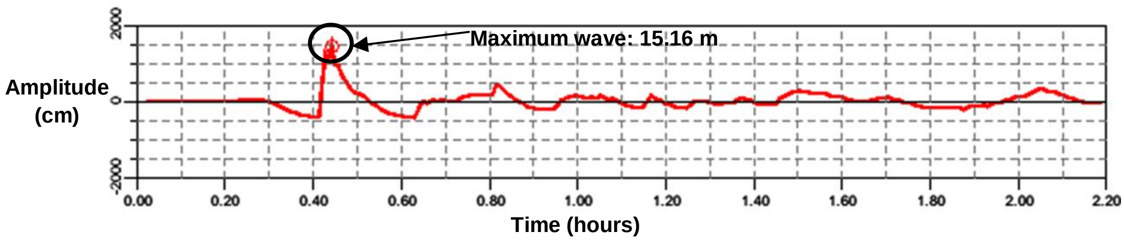

Figure 11. Maximum wave-height arriving at Zar-Abad breakwater.

PROBABILISTIC TSUNAMI HAZARD ASSESSMENT & RESULTS

Subsequently, the probabilities of tsunami wave exceeding certain heights are derived, as presented in the following figures 12 to 19. Evidently, at Jask, Konarak, and Beheshti ports the probability of tsunami waves exceeding 1 (m) becomes close to zero, while Zar-Abad experiences relatively large tsunami amplitudes of larger than 5 (m), associated with a 20% probability during the next 100 years (Figure 19). For the sake of comparison, while the probability of wave exceeding 2 (m) is almost zero for many of the considered breakwaters, such probability is about 40% at Zar-Abad.

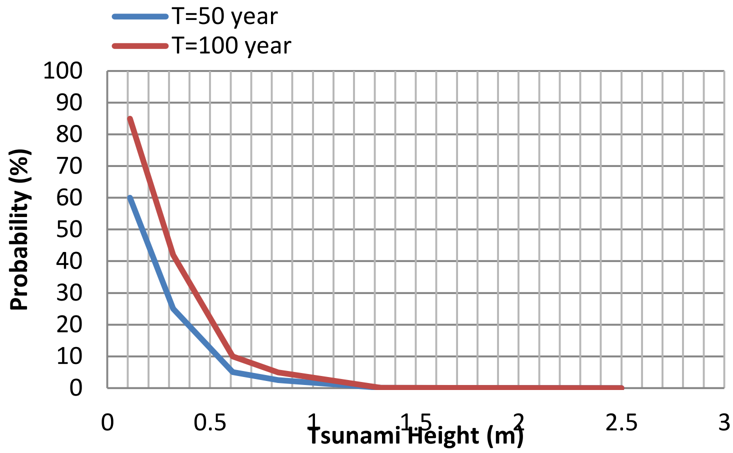

Figure 12. The probabilities of tsunami wave-heights exceeding certain values in the next 50 & 100 years at Beheshti breakwater.

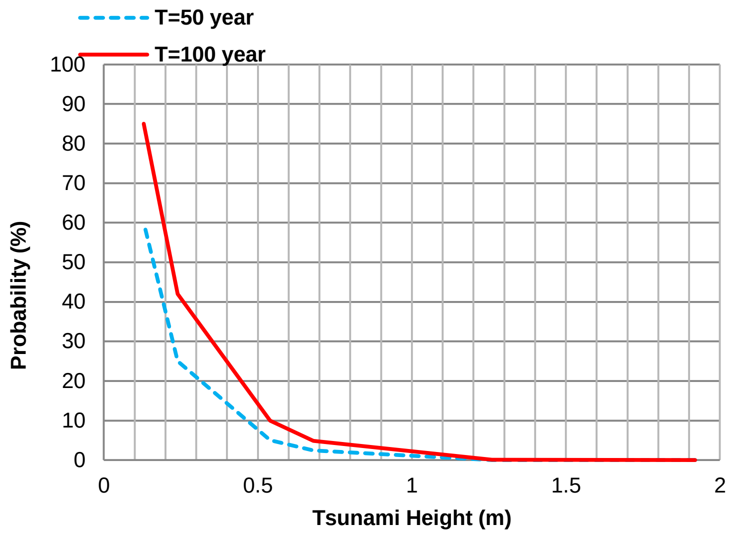

Figure 13. The probabilities of tsunami wave-height exceeding certain values in the next 50 & 100 years at Jask breakwater.

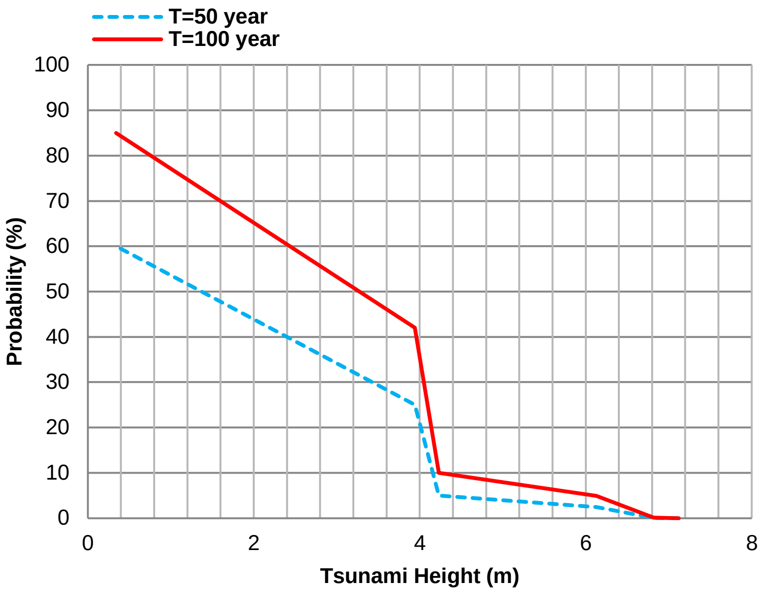

Figure 14. The probabilities of tsunami wave-heights exceeding certain values in the next 50 & 100 years at Karati breakwater.

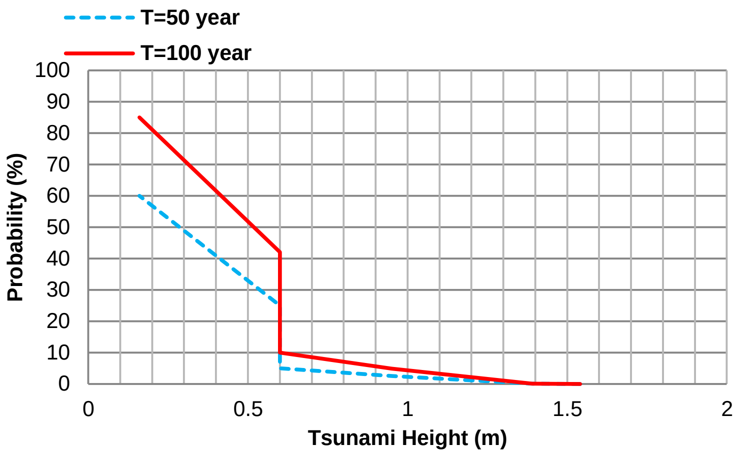

Figure 15. The probabilities of tsunami wave-heights exceeding certain values in the next 50 & 100 years at Konarak breakwater.

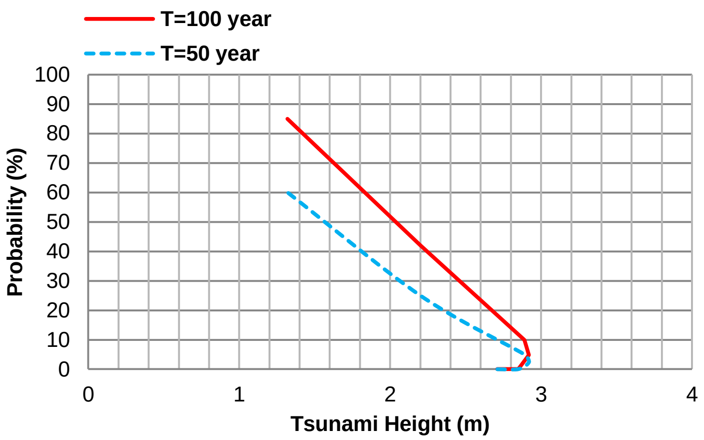

Figure 16. The probabilities of tsunami wave-height exceeding certain values in the next 50 & 100 years at Pasa-Bandar breakwater.

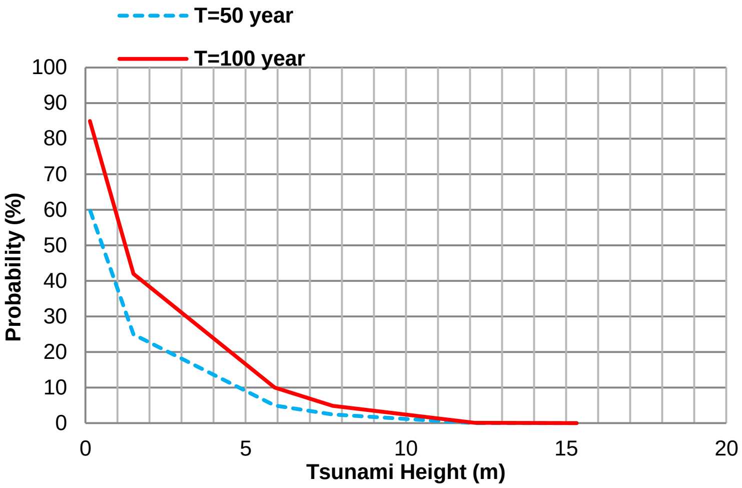

Figure 17. The probabilities of tsunami wave-heights exceeding certain values in the next 50 & 100 years at Zar-Abad breakwater.

BREAKWATERS SEA-SIDE & LEE-SIDE STABILITY ANALYSIS

Although, significant developments have been reported with respect to reliable design of vertical breakwaters and rubble-mound structures against wind waves and swells, however, in relative terms few formulae have been established specifically for the design of armor units of tsunami impacted rubble-mound breakwaters.

Esteban *et al.* (2012) have proposed a modification to the Hudson formula which may be employed for the design of the sea-side armor units of breakwaters in tsunami impacted regions. Based on their advocated methodology, two formulas associated with two different levels of risk may be utilized, based on the so-called 'tenacious structure' concept, *a.k.a.* a 'resilient structure', representing a slowly and partially failing structure when subjected to the less frequent, catastrophic so-called level 2 events, such as the 2004 Indian Ocean or the 2011 Great Eastern Japan tsunamis.

As customary in performance-based analysis, level 1 events of an expected probability of occurrence over the useful lifetime of structures shall usually be expected to result in little or no damage due to the social and/or economic value of the structure and its intended function, however, the associated construction costs are almost always deemed a major inhibiting factor to expect no major failure under level 2 cases. Typically, for tsunami risk assessment related purposes, according to the above-mentioned research by Esteban *et al.* (2012), the Japanese practice reportedly associates return periods ranging from about 50 at the lower end, up to around 150 years to define the level 1 scenario, in which case no damage shall usually be expected, while the level 2 category for tsunamis is often reserved for return periods starting from at least 150 years to over a few thousand years; where some degree of structural failure inadvertently needs to be permitted. To strive for striking a right balance in related cost-benefit analysis, the below equations as supported by hydraulic model test results, may be utilized:

$$\text{Level 1}: \quad W = \frac{\gamma H_{tsunami}^3}{K_D (S_D - 1)^3 \cos\alpha} \tag{1}$$

$$\text{Level 2}: \quad W = 0.25 \frac{\gamma H_{tsunami}^3}{K_D (S_D - 1)^3 \cos\alpha} \tag{2}$$

, where W , $H_{tsunami}$, γ , S_D , α, and K_D respectively denote the average armor unit weight (tons), the design tsunami wave-height (m), the density of armor (tons/m³), the relative underwater density of armor (tons/m³), the angle of the front slope of the structure with respect to the horizontal, and an empirically determined damage coefficient.

Due to the active presence of wind-waves and regular monsoon season swells every year at the MSD region, as well as a few recorded tropical cyclones occurring in the current and last century, such as ‘Gonu’ and ‘Phet’, which impacted the region of interest in 2007 and 2010, respectively, it is imperative for regional development policy purposes to evaluate the earlier designs of existing breakwaters, some of which have been in service for almost half a century with little or no need for repair, with the associated design criteria having been solely concerned with Monson waves, considering future tsunami events according to the above-mentioned methodology.

Similarly, lee-side breakwater stability after the passage of tsunami may also be checked via below Izbash relation (Equation 3), as advocated by Schiereck (2003):

$$U = 1.2\sqrt{2\Delta g\, d_n} \tag{3}$$

, where U , g , Δ, and d_n stand for the tsunami flow velocity, gravitational acceleration (m/s^{-2}), relative underwater density of armor and the nominal armor unit diameter (m), respectively.

Evidently, after estimating the tsunami flow velocity according to MLIT (2009) from the water surface elevation due to tsunami (η) and water depth (h), above-mentioned Izbash relation may be solved to derive the stable lee-side armor unit weights:

$$U = \eta\sqrt{\frac{g}{h}} \tag{4}$$

RESULTS & DISCUSSIONS

In brief, considering the level 1 event the sea-side armor layers of all six afore-mentioned breakwaters were shown to be stable under tsunami impact, while ascertaining the fulfillment of the so-called tenacious structure requirement according to which the structure would fail gradually and partially under the impact of a level 2 event is contingent upon further research regarding the definition of the level 2 tsunami scenario attributable to MSD.

Relatively, the lee-side armor layer stability condition of all breakwaters is evidently the more vulnerable issue as filter grade stone designed for waves inside harbors may indeed be deemed weak against tsunami currents. Notably, at Pasa-Bandar, Zar-Abad and Karati breakwaters lee-side stability against the level 1 tsunami current is not satisfied under the Izbach tsunami flow velocity criterion.

While in theory it is possible to achieve stability for the lee-side of Karati breakwater using average armor unit weights of about 7 (tons), sound social and economic justification is a pre-requisite prior to implementing such a design. Rather more drastically, with respect to the case of Zar-Abad and particularly more so for Karati breakwater, the required stable stone weights against tsunami current force are simply too high and impractical, considering the yield of the local quarries.

Generally, due to relatively lower level 1 tsunami wave-heights anticipated to arrive at the region under study in contrast to Monsoon swells and tropical storms generated waves, the latter are seen to be determinative for design of a stable armor layer. However, tsunami flow velocity will be critical for structural stability of the lee-side of all these breakwaters where structural free-board is selected to limit overtopping by Monsoon season waves.

Additionally, it deserves mention that Konarak port by virtue of being situated inside the Chabahar bay is relatively sheltered also from tsunami impact along some initial segments of the breakwater. Finally, as a result of Shahid Beheshti breakwater being situated in fairly deep waters, therefore relatively less significant tsunami impact is expected at that location prior to the onset of more substantial shallow-water shoaling.

In continuation, while it is hoped that the presented results may serve as a stepping-stone for future endeavors regarding design of resilient coastal and port structures in the region, however, the sheer need for a thorough characterization of MSD tsunami-genic characteristics needs to be underscored.

ACKNOWLEDGEMENTS

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