Chapter 6
Tsunami Risk, Preparedness and Warning System in Pakistan

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Abstract This chapter presents a review of the tsunami risk posed to the southern coasts of Pakistan and Iran by potential earthquakes from the Makran subduction zone and also presents a structure for a regional tsunami warning system. Historical data of earthquake in the Makran region shows that the region is susceptible to large earthquakes which are capable of producing destructive tsunamis. Tsunami hazard in the region can be classified into three levels based on the sizes of the earthquakes used for tsunami hazard assessments: (1) characteristic earthquake with magnitude *Mw*8.1, (2) maximum regional earthquake with magnitude *Mw*8.3, and (3) worst-case earthquakes with magnitudes *Mw*8.6 and *Mw*9.0. The aforesaid earthquakes produce wave heights up to 7, 9, 10 and 18 m at the coastlines of the Makran region. We propose a tsunami warning system in the region based on seismic waveforms and using a database of precalculated tsunami scenarios. At least 2 deep-water tsunami gauges and 50 coastal gauges are necessary for tsunami understanding and warnings in the region. Any tsunami warning system in the region needs strong international cooperation between the countries in the region.

Keywords Makran subduction zone • Northwestern Indian Ocean • Tsunami • Earthquake • Tsunami hazard assessment • Tsunami warning system

6.1 Introduction

The recent large tsunamis of 2011 Tohoku and 2004 Sumatra tsunamis have awakened the attention of international community to large hazards posed by tsunamis. The extensive destruction and death caused by these tsunamis showed that world's coastal communities are rather vulnerable to tsunamis, even in Japan where decades of tsunami education and a sophisticated tsunami warning system was in effect prior to the 2011 tsunami attack. The fact that both tsunamis occurred in tectonic settings that were not expected to produce $M9^{+}$ earthquakes (Okal et al. 2013), indicates that

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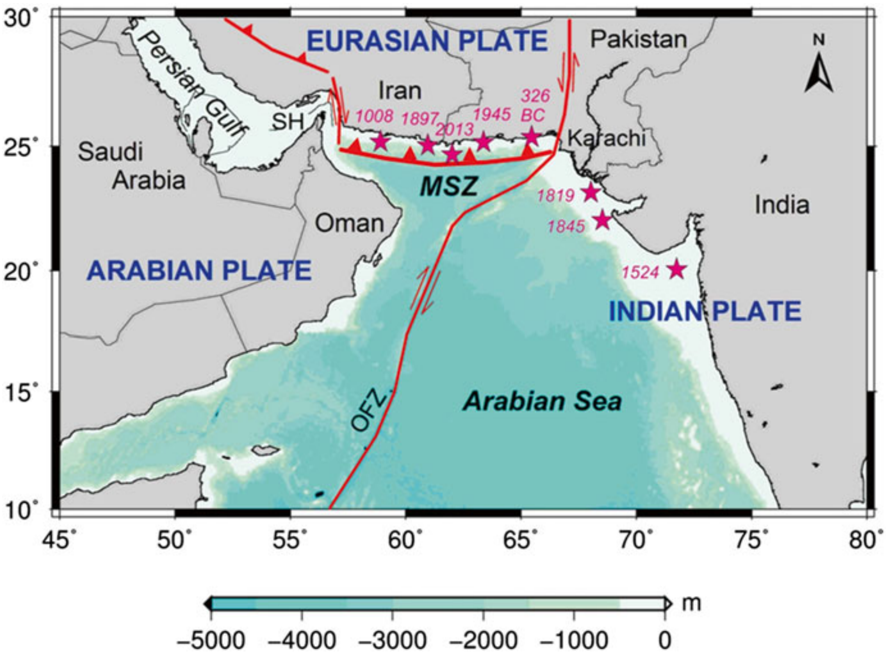

Fig. 6.1 General location map of the Makran subduction zone (MSZ) at the northwestern Indian Ocean showing the locations of past tsunamis reported in the region (*purple asterisks*). Abbreviations are: *MSZ* Makran subduction zone, *OFZ* Owen fracture zone, *SH* Strait of Hormuz (Updated from Heidarzadeh et al. 2009a)

it is too simplistic to categorize world's subduction zones into those capable and incapable of producing large earthquakes. According to McCaffrey (2007), every subduction zone is dangerous and it is wrong to focus on some and ignore some others. This is a basic lesson from the 2011 Tohoku and 2004 Sumatra tsunamis.

Makran subduction zone (MSZ), offshore southern coasts of Iran and Pakistan (Fig. 6.1), is an example of those subduction zones whose tsunami hazards were underestimated or ignored before the 2004 Sumatra large tsunami. With a length of around 1,000 km, MSZ is formed by the northward subduction of the Arabian plate beneath the Eurasian plate at the rate of around 19 mm/year (Heidarzadeh et al. 2009b). The region experienced a large tsunami which left a death toll of around 4,000 on 27 November 1945 (Heck 1947). The parent earthquake was of *Mw*8.1 (Byrne et al. 1992) which is the largest instrumentally-recorded earthquake so far in the Makran region. This indicates that the region is potentially susceptible to large tsunami-genic earthquakes. In addition to tectonic tsunamis, the region is also at the risk of meteo-tsunamis. The cyclone Gonu in 2007 caused severe inundation and damage in the region (Fritz et al. 2010). It is discussed later that other evidence of meteo-tsunamis has been found in the region. The Makran region is also susceptible to landslide tsunamis; even due to inland earthquakes. Heidarzadeh and Satake (2014) showed that an inland *Mw* 7.7 earthquake in Pakistan triggered a landslide tsunami in the Makran region.

In this chapter, we address tsunami hazards in the northwestern Indian Ocean. We first present a summary of historical tsunamis reported in the region followed by different scenarios for tsunami hazard assessment. Finally, we discuss preparedness for tsunami and tsunami warning system for the region.

6.2 Historical Tsunamis in the Region

Historical tsunamis in the region have been studied by Heidarzadeh et al. (2008a) and (2009a) which are shown in Fig. 6.1 by purple asterisks. Table 6.1 presents the details of each event. However, it should be noted that these event are coming with different levels of confidence factors. Such a high level of uncertainties about the veracity of historical tsunamis in the region shows that the available information about tsunami is poor and historical archival and paleo research is necessary for the Makran region.

Besides the fact that the data on historical events is incomplete and needs more supporting works, the current data in Table 6.1 shows that the region is susceptible to different kinds of tsunamis: tectonic, volcanic, landslide and meteorologic tsunamis (Heidarzadeh et al. 2008a). Our limited data (Table 6.1) shows that similar to other tsunamigenic zones in the world, the most common type of tsunami source is

Table 6.1 List of tsunamis reported in the northwestern Indian Ocean (Updated from Heidarzadeh et al. 2008a)

No.	Year	Location	Earthquake magnitude	Type of Tsunami source	Loss of life	Runup (m)	CF[a]
1.	326 BC	–	–	Earthquake	–	–	1
2.	1008	–	–	Earthquake	1,000[b]	–	2
3.	1524	Gulf of Cambay	–	Earthquake	–	–	1
4.	1819	Rann of Kutch	7.5–8.25	Landslide/Volcano	>2,000[b]	–	2
5.	1845	Rann of Kutch	>6	Landslide/Volcano	–	–	2
6.	1897	–	–	Volcani/ Meteorologic	–	–	1
7.	1945	63.0°E 24.5°N	8.1–8.3	Earthquake	4,000[b]	5–12	3
8.	2013[c]	61.49°E 24.62°N	–	Landslide	0	<1	3

[a]Heidarzadeh et al. (2008a) assigned a confidence factor (CF) to each event whose value indicates probability of actual tsunami occurrences. They defined it as: (1) probable tsunami; (2) definite tsunami but the generation mechanism and location are not certain, and (3) instrumentally recorded tsunami
[b]Both by earthquake and tsunami
[c]According to Heidarzadeh and Satake (2014)

the tectonic source. The archival research by Heidarzadeh et al. (2008a) showed that the event of 1897 was possibly of volcanic/meteorologic origin; similar to the cyclone Gonu in 2007 which generated large inundation (Fritz et al. 2010). Landslide sources also seem to be responsible for some tsunamis both independently (e.g., the 1819 event) and in combination to a tectonic source (e.g., events of 1945 and 2013). There have been reports that a landslide source contributed to the tectonic source of the 1945 Makran tsunami as submarine telegraph lines offshore Pakistan were ruptured following the earthquake (Heidarzadeh et al. 2008a). A landslide triggered by *Mw* 7.7 Pakistan inland earthquake, generated a small tsunami with runup heights less than 1 m in the Makran region (Heidarzadeh and Satake 2014).

6.3 Scenarios for Tsunami Risk Assessment

Tsunami hazard assessment for tectonic tsunamis strongly depends on the size of the earthquake scenario used for assessment. It is evident that the larger the earthquake size, the larger the tsunami that is produced. In this context, there are standards as per how to select the earthquake size for tsunami hazard assessment. Three different levels of earthquake sizes have been usually used worldwide for earthquake and tsunami hazard assessments: (1) characteristic earthquakes, (2) regional maximum earthquake, and (3) worst-case earthquakes (Okal and Synolakis 2008). Each of these levels can be used for some particular applications. Below, each of these classes is discussed and the resulting tsunami waves are presented.

6.3.1 Characteristic Earthquake

By definition, a characteristic earthquake is an earthquake with a certain size that occurs with regular intervals in a region. Usually, instrumental, historical and paleoseismological studies are conducted to define the characteristic earthquake for a particular region. For a region like MSZ where the available information about past seismicity is poor, the maximum recorded earthquake in the region was assumed as the characteristic earthquake (Heidarzadeh et al. 2009a). The Makran earthquake of 27 November 1945, with a moment magnitude of *Mw*8.1, is the maximum recorded earthquake in the region whose return interval was estimated in the range of 150–250 years (Page et al. 1979; Heidarzadeh et al. 2008b). According to Heidarzadeh et al. (2009a), such an earthquake is capable of rupturing about 150 km of the Makran plate boundary. Therefore, this characteristic earthquake was moved along the plate boundary and the resulting tsunamis were calculated. Figure 6.2 shows the results of tsunami coastal wave amplitudes for the characteristic earthquake (*Mw*8.1) which shows that the tsunami wave heights reach up to 6–7 m along the southern coasts of Iran and Pakistan.

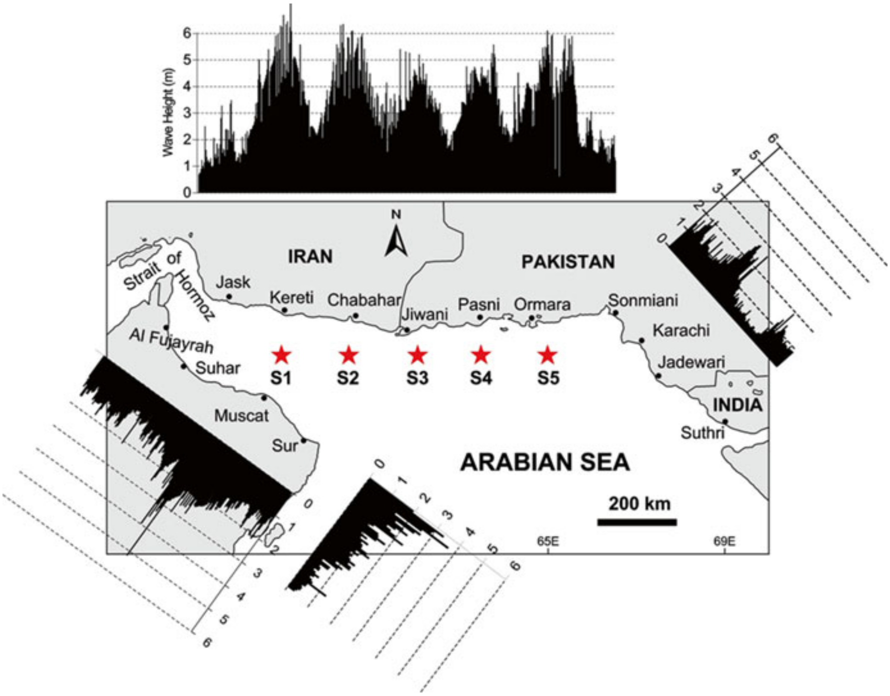

Fig. 6.2 Distribution of maximum positive tsunami amplitudes along various Makran coasts for five scenarios of characteristic earthquake. All scenarios of S1-S5 are earthquakes of magnitude *Mw*8.1 (After Heidarzadeh et al. 2009a)

6.3.2 Maximum Regional Earthquakes (M_{max})

A slightly more conservative method for tsunami hazard assessment is to base the assessment on the regional maximum earthquake (M_{max}). Probabilistic methods can be used to define M_{max} which apply earthquake catalog for any particular region to calculate maximum earthquake (e.g., Kijko 2004). A catalog of earthquakes at the Makran region has been compiled by Heidarzadeh and Kijko (2011) containing 453 events in the magnitude range of 3.0–8.1. The results of probabilistic seismic hazard assessment for the Makran region shows that the maximum regional earthquake in the region is estimated around 8.3. Such an earthquake has a return period of around 1,000 years. The probability for occurrence of such an earthquake in next 50 years is around 5 % which is a low probability. It is clear that any tsunami hazard assessment based on M_{max} is relatively conservative given the low occurrence probability of such an earthquake. According to Heidarzadeh et al. (2008b), the maximum tsunami wave height is up to 8–9 m along the southern coasts of Iran and Pakistan.

6.3.3 Worst-Case Scenarios

The 2004 Sumatra and 2011 Tohoku events are two recent examples showing that worst-case scenarios occur (Okal and Synolakis 2008). Although tsunami planning based on worst-case scenarios seems to be expensive, application of worst-case scenarios is inevitable in some cases. Two worst-case scenarios for the Makran region are studied by Heidarzadeh et al. (2009b) which consists of earthquakes with magnitudes 8.6 and 9.0 rupturing half and full subducting boundaries, respectively. According to Heidarzadeh et al. (2009b), the resulting tsunamis reach maximum heights of 8–10 and 15–18 m for the aforesaid two earthquakes, respectively.

6.3.4 Summary of Different Scenarios

A summary of tsunami hazard assessments using different levels of earthquake sizes are presented in Table 6.2. As discussed earlier, for different purposes, one of the levels of assessment can be used. For example, for planning residential areas, application of maximum regional earthquake is appropriate, but for planning the location of nuclear power plants, a worst-case scenario is preferable. Making any decision about which level of tsunami hazard assessment to be used for planning and mitigation purposes depends on local authorities and special characteristics of each coastal area.

Table 6.2 Different tsunami scenarios used for investigating tsunami hazard assessment in the Makran subduction zone and the results

Type of scenario	Earthquake size	Maximum wave height in Iran (m)	Maximum wave height in Pakistan (m)	Maximum wave height in Oman (m)
Characteristic earthquake (Fig. 6.2) (Heidarzadeh et al. 2009a)	*Mw* 8.1	7.0	6.0	5.0
Maximum regional earthquake (Heidarzadeh et al. 2008b)	*Mw* 8.3	9.0	7.0	7.0
Worst-case scenario (Heidarzadeh et al. 2009b)	*Mw* 8.5	10.0	10.0	10.0
	Mw 9.0	18.0	18.0	18.0

Heidarzadeh et al. (2008a, 2009a)

6.4 Tsunami Preparedness for the Region

A number of actions have been taken in order to provide preparedness against tsunamis in tsunami-prone regions. The most important of these actions are as follows:

6.4.1 A Tsunami Warning System

Two main tsunami warning systems, currently operational in the world, are: Pacific Tsunami Warning System (PTWS) operated by US National Oceanic and Atmospheric Administration (NOAA) and Japan tsunami warning system operated by Japan Meteorological Agency (JMA). Apart from some differences, tsunami forecast both in PTWC and JMA is based on pre-calculated tsunami databases. In JMA system, first, earthquake magnitude and epicenter is estimated using seismic waveforms and then, the database of pre-calculated tsunami scenarios are used to estimate the tsunami height along the coastlines. In fact, JMA tsunami warning system in based on seismic waveforms to forecast tsunami for the near-field. They monitor coastal tsunami wave heights to update tsunami warnings, however, tsunami waveforms does not play a major role in this tsunami warning system. This algorithm needs less than 10 min to issue tsunami warnings.

For PTWC, the pre-calculated tsunami waves are based on unit slip sources on different segments of subduction zones which are called “Green’s functions”. The subduction boundaries, with known historical records of tsunami, are divided into segments of length 50 km or less. Then, tsunami green functions are calculated at offshore locations. In case of a tsunami, at the beginning, earthquake epicenter and magnitude is estimated using seismic waveforms. Then tsunami waveforms recorded at offshore locations (DART stations) are used to constrain the tsunami source using an inverse algorithm. Such an algorithm needs around 1 h to issue tsunami warnings and is useful mostly for far-field tsunamis.

It can be seen that the vital part of each of them is earthquake magnitude estimation. The main reason for JMA’s inaccurate warnings during the 2011 Tohoku tsunami was inaccurate earthquake magnitude estimation (Ozaki 2011). In this context, the PTWC algorithm is less sensitive to earthquake estimation because any observation by PTWC is evaluated using tsunami waveforms. However, the PTWC method is not applicable to near-field tsunamis.

For the Makran region, a tsunami warning system similar to JMA seems appropriate because the only risk in this region is from near-field tsunamis. Therefore, a tsunami warning system in this region needs to be based on seismic waves. However, any tsunami in the Makran region may also cause some damages in the southern Indian Ocean because at least 8 countries are at risk of far-field tsunami hazard from this region; therefore, such a system may also provide warnings for those distant coasts (Fig. 6.3).

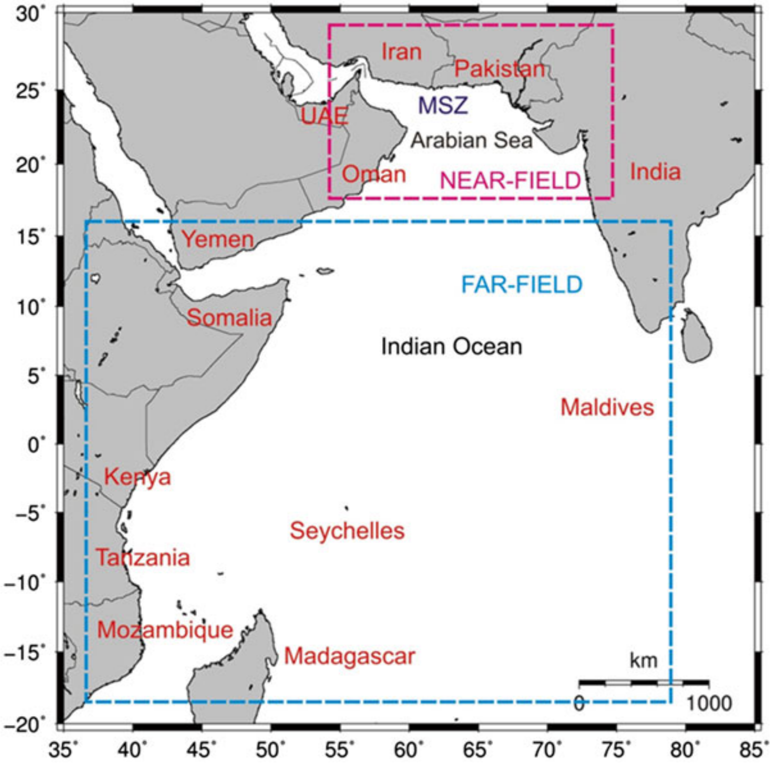

Fig. 6.3 Near-field and far-field tsunami hazards from Makran subduction zones

6.4.2 *Tsunami Infrastructures*

A tsunami warning system needs to be accompanied by a number of infrastructures among which are:

6.4.2.1 Deep-Water Tsunami Gauges

Deep-water tsunami gauges provide timely and refined information about tsunami. Although they may not be useful for warnings to the near-field, they are very useful for the far-field warnings. In addition, they provide useful information for tsunami research and help to better understand tsunami behavior in the region. At least two deep-water gauges are recommended; one for eastern part offshore Pakistan, and the other for the western part offshore Iran.

6.4.2.2 Coastal Tsunami Gauges

An array of at least 50 coastal tsunami gauges is necessary in the coastal areas of Iran, Pakistan, Oman, United Arab Emirates, and India. Currently, some tide gauges are available in the region; however, few of them are working well and the data is not shared between these countries. Strong international cooperation is necessary for installation of the gauges and for sharing the data.

6.4.2.3 Tsunami Inundation Maps

Tsunami inundation maps show which parts of the coast and how far from the shoreline is inundated by tsunami. It is evident that the extent of inundation depends on the earthquake scenario; the larger the earthquake, the larger the inundated area. Therefore, first, the appropriate earthquake scenario needs to be decided, and then, inundation maps can be developed. Examples of inundation maps for the region are presented by Heidarzadeh et al. (2009b) in four major cities in the region: Chabahar (Iran), Pasni (Pakistan), Karachi (Pakistan) and Muscat (Oman) by assuming a worst-case scenario with magnitude 9.0 in MSZ.

6.4.2.4 Tsunami Signage

The coastal zones at risk of tsunami need to be equipped with appropriate tsunami warning and evacuation signage. In addition, some of this signage also can give some education to local and non-local people. An example of tsunami signage is shown in Fig. 6.4.

Fig. 6.4 An example of tsunami signage (https://www.flickr.com/photos/debaird/540858467/in/photostream/)

6.4.3 Education

Experiences from past tsunamis have shown that education is an important part of any tsunami-resilient community (Bernard 2005). In some cases small pieces of tsunami education have saved many lives during tsunamis (e.g., Fritz and Kalligeris 2008). According to McCaffrey (2007), a 10-years old British girl in Thailand saved some lives during the 2004 Sumatra tsunami by little knowledge that she had learnt in school about tsunamis. Tsunami education is rather efficient for near-field tsunamis as the time for warning is so short. Education may be given to coastal communities in several ways including:

- information is school books
- TV and radio programs and videos
- newspapers, newsletters
- workshops, seminars and short courses
- signage in streets
- maps

6.5 Summary

A summary of tsunami hazard in the Makran subduction zone was presented. Tsunami hazard in the region can be classified into three levels based on the sizes of the earthquakes used for tsunami hazard assessments: (1) characteristic earthquake with magnitude $Mw8.1$, (2) maximum regional earthquake with magnitude $Mw8.3$, and (3) worst case earthquakes with magnitudes $Mw8.6$ and $Mw9.0$. The aforesaid earthquakes produce wave heights up to 7, 9, 10 and 18 m at the coastlines of the Makran region. We propose a tsunami warning system in the region based on seismic waveforms and using a database of pre-calculated tsunami scenarios. At least 2 deep-water tsunami gauges and 50 coastal gauges are necessary for tsunami understanding and warnings in the region. Any tsunami warning system in the region needs strong international cooperation between the countries in the region.

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