New insights into the source of the Makran tsunami of 27 November 1945 from tsunami waveforms and coastal deformation data

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Source of the Makran tsunami of November 1945

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Abstract

We constrain the source of the 27 November 1945 tsunami in the Makran subduction zone (MSZ) using available tsunami waveforms recorded on tide gauges in Mumbai (India), Karachi (Pakistan), and that inferred in Port Victoria (Seychelles) and co-seismic deformation data along the Makran coast. Spectral analysis of the tsunami waveforms showed that the tsunami governing period was 40-50 min in Karachi whereas it was around 22 min in Mumbai. The inferred tsunami waveform in Port Victoria also indicated a period of around 21 min for the tsunami. Tsunami numerical simulations from the previously-proposed source models failed in reproducing the observed tsunami waveforms and co-seismic deformation data. Sensitivity analysis showed that the source fault needs to be extended offshore into the deep water in order to reproduce the first 22-min signal in Mumbai. Based on the inversion of the observed tsunami waveforms, we propose a 4-segment fault with varying slip amounts as the final source. This source includes a slip of 4.3 m onshore near Ormara (Pakistan) and a slip of 10 m offshore at the water depth of around 3000 m. The total fault length is 220 km and average slip is 6.1 m. This source, first, reproduces fairly well the observed tide gauge records in Mumbai and Karachi; second, produces ~1 m of uplift in Ormara and ~1 m of subsidence in Pasni; and third, gives a moment magnitude of 8.3 for the earthquake which is in the acceptable range of seismic data. The computed 1 m of uplift in Ormara is in the range of the reported uplift of 1-3 m in the literature. As the tide gauge stations were located in the far-field, our proposed source explains mainly the tectonic source of the tsunami.

1. Introduction

The Makran tsunami of November 1945 is of the utmost importance for studying tsunami hazards in the northwestern Indian Ocean as it is the largest instrumentally-recorded tsunami in the region. The tsunami, generated by an M 8.0-8.3 earthquake (BYRNE et al. 1992; RICHTER 1958) at the Makran subduction zone (MSZ), caused extensive damages and a death toll of 4000 in the near field (HECK 1947) (Fig. 1). In the far-field, it caused about 10 fatalities in Mumbai (NATURE 1945) and generated a wave height of about 30-50 cm in Seychelles about 3300 km away from the tsunami source (BEER and STAGG 1946). The earthquake origin time was 21:56 GMT on November 27 and the epicenter was at around 63.48ºE and 25.15ºN (BYRNE et al. 1992) (Fig. 1). As this event was the largest recorded earthquake in the region, it has been employed as the characteristic event for earthquake and tsunami hazard assessments for the Makran region.

There have been different reports about the magnitude of the 27 November 1945 Makran earthquake: M 6.7 by PENDSE (1946), M $8\frac{1}{4}$ by GUTENBERG and RICHTER (1954), M 8.3 by RICHTER (1958), and M 8.3 by DUDA (1965). Seismic waveform inversion by BYRNE et al. (1992) resulted in a moment magnitude range of 8.0-8.24 which led them to an average magnitude of 8.1 for this earthquake. Thus, the magnitude from seismic analysis ranges 8.0 – 8.3.

The 1945 Makran tsunami has been studied by several authors. HEIDARZADEH et al. (2008a) performed a numerical modeling of the tsunami in order to interpret historical observations. NEETU et al. (2011) studied the trapped tsunami waves recorded on tide gauges in Karachi and Mumbai. JAISWAL et al. (2009) modeled this tsunami to study its effects on the Indian coasts. HEIDARZADEH et al. (2009a) studied the tsunami hazards associated with the MSZ by assuming a 1945-type earthquake as the characteristic tsunamigenic-earthquake for the region. In some of the above studies, the tsunami source parameters were based on the seismic

study by BYRNE et al. (1992). Details of the sources proposed by the aforesaid authors are summarized in Table 1 and are schematically shown in Fig. 2a. Table 1 implies that the source parameters used by different authors significantly differ from each other. As an example, HEIDARZADEH et al. (2008a) assumed a slip of around 7 m on very shallowly dipping fault plane which generated a maximum seafloor deformation of around 2 m resulting in a tsunami runup height of around 1 m in Kutch (Figs. 5-6 in HEIDARZADEH et al. 2008a). But JAISWAL et al. (2009) assumed a slip of around 15 m which generated a seafloor deformation of 6-7 m resulting in a runup height of around 3-4 m in Kutch (Figs. 3a-4 in JAISWAL et al., 2009).

Such a significant difference among the fault parameters of the 1945 Makran earthquake in previous studies can be problematic because this event has been used as the characteristic event for tsunami hazard assessment. This problem may partly arise from the unavailability of any tide gauge records of this tsunami; however, NEETU et al. (2011) recently published two tide gauge records at Mumbai and Karachi. In addition, the available co-seismic deformation data was not used by the aforesaid authors to constrain the tsunami source. In such a context, this study is aimed at constraining the source of the 1945 Makran tsunami using available tide gauge records in Mumbai and Karachi, an inferred sea level record in Port Victoria (Fig. 1) as well as available field data on co-seismic uplift/subsidence reported by PAGE et al. (1979). In the following, we apply spectral analysis to the tsunami waveforms, and then perform dislocation modeling of the earthquake fault and numerical modeling of tsunami waves to examine how they can help to constrain the tsunami source.

2. Tsunami hazards in the Makran region

The tsunami hazards in the Makran region have been studied through different methods including archival, geological, and numerical methods with emphasis on the November 1945 Makran tsunami. The geological field study by PAGE et al. (1979) showed that the region has

experienced large-magnitude earthquakes as large as the 1945 event with a recurrence interval of around 125-250 years. Possibility for the occurrence of large-magnitude earthquakes in Makran was emphasized by QUITTMEYER and JACOB (1979) through a comprehensive seismological study. The mechanism of the 1945 earthquake was studied by BYRNE et al. (1992) through inversion of seismic body waves indicating that the earthquake was of size of Mw8.1 and ruptured around one-fifth of the subduction zone, i.e., ~ 200 km. The seismogenic potential of the MSZ was studied by SMITH et al. (2013) by analyzing the thermal structure of the subduction zone. HOFFMANN et al. (2013) conducted a detailed archival study to document the effects of the 1945 tsunami on various coastlines of the Makran region and interviewed elderly eyewitnesses of this tsunami on the coast of Oman. HEIDARZADEH et al. (2008a,b & 2009a,b) and HEIDARZADEH and KIJKO (2011) studied the tsunami hazards associated with the MSZ using deterministic and probabilistic methods. By providing seismic reflection profiles of the MSZ, MOKHTARI (2014) studied the effect of possible splay faulting on tsunami hazards in the region. Geological studies on tsunami deposits by RAJENDRAN et al. (2013) led them to conclude that the western part of Makran is prone to large earthquakes. SHAH-HOSSEINI et al. (2011) conducted a field survey of the Iranian coast of Makran and concluded that the origin of large coastal boulders was tsunami. Sedimentological studies by DONATO et al. (2009) and PILARCZYK and REINHARDT (2012) located the deposits of the 1945 Makran tsunami in Sur Lagoon, Oman. The coast inside the Gulf of Oman was impacted by cyclone Gonu in 2007 (FRITZ et al. 2007) and to a lesser extent by the 2004 Indian Ocean tsunami. Recently, a small tsunami was recorded in the region possibly due to a submarine landslide following Pakistan Mw 7.7 inland earthquake showing that even inland earthquakes can trigger landslide tsunamis in the Makran region (HEIDARZADEH and SATAKE 2014). The Makran region is also at risk of far-field tsunamis (e.g., OKAL et al. 2006). This short summary of the available literature on the tsunami hazards in MSZ indicates that the region has been home of large tsunamigenic earthquakes in the past.

3. Data

The data used here to constrain the tsunami source are of two types: (1) tsunami waveform data, and (2) co-seismic deformation data. They are briefly introduced below.

3.1. Tsunami waveforms

Our tsunami waveform data are those recorded on tide gauges in Mumbai (India) and Karachi (Pakistan) and one described in Port Victoria (Seychelles). The two tide gauge records have been recently retrieved by NEETU et al. (2011) (Fig. 2b-c). As shown, the Karachi tide gauge was out of order within the first hour after the earthquake; then started recording the waves. According to NEETU et al. (2011), the tide gauge started recording before the arrival of the first wave. However, it is not known whether the early part of the tsunami waveform was recorded correctly or not. The two waveforms in NEETU et al. (2011) were digitized with the sampling interval of 1.5 min, and were de-tided using the tidal analysis package TASK (Tidal Analysis Software Kit) developed at the Proudman Oceanographic Laboratory (UK) (BELL et al. 2000).

The descriptive sea level change in Seychelles was reported by BEER and STAGG (1946) as follows: *"The Chief Meteorological Officer, Royal Air Force East Africa, has reported an interesting tidal irregularity observed by Captain A. Sauvage, port officer at Port Victoria, Mahe, Seychelles, on November 28, 1945, at about 10 a.m. local time. It appears that while the normal water-level corresponding with the state of tide at this time was 1.5 in. [~ 4 cm], the level observed at 9 hr. 47 min. a.m. was 12 in [~ 31 cm]. The water then rose to 18 in. [~ 46 cm] at 9 hr. 52 min., dropped to 0 at 10 hr. 5 min. and rose again to 14.5 in. [~ 37 cm] at 10 hr. 13 min. a.m."* This observation, which contains four sea level points at different times,

6

is schematically shown in Fig. 2d indicating a tsunami period of around 21 min for the sea level oscillations in Seychelles.

3.2. Co-seismic deformation data

The co-seismic deformation data are based on the geological field survey of the region by PAGE et al. (1979) which was conducted approximately 30 years after the earthquake. This field data indicates that Pasni experienced significant subsidence so that the coastline was moved about 100 m landward. PAGE et al. (1979) speculated that this subsidence was apparently generated by a submarine slide. PAGE et al. (1979) also reported an uplift of about 1-3 m in Ormara (Figs. 1 and 2e). This uplift data was the results of interviews with local fishermen and was the difference between tidal levels before and after the earthquake. It is clear that these measurements were associated with some errors but no discussion was made by PAGE et al. (1979) about the amount of possible errors or how many sites were surveyed to reach this uplift value.

4. Methodology

Different methods have been applied in the past to obtain information about the tsunami source from its sea level records such as Fourier analysis (e.g., RABINOVICH 1997), wavelet analysis (e.g., HEIDARZADEH and SATAKE 2013a; BORRERO and GEER 2013), forward tsunami modeling (e.g., TINTI et al. 1999), and tsunami waveform inversion (e.g., SATAKE et al. 2013) . Here, our method is a combination of the aforesaid methods. When the available observations are limited (like this study), application of tsunami waveform inversion alone is not fruitful because the stations used for inversion should provide adequate azimuthal coverage. It is evident that the observations available in this study do not provide adequate azimuthal

coverage because only two waveforms are available: one at the east (i.e., Karachi) and the other at the south-east of the source (i.e., Mumbai). In this case, a combination of forward and inverse methods may provide more insights. Using forward modeling, the location of the tsunami source and fault parameters are fixed; then the slip distribution is calculated on the fault plane using waveform inversion. In fact, this method is a constrained inversion. We briefly discuss each method in the following.

4.1. Spectral analysis

Two types of spectral analysis have been performed in this study: Fourier and wavelet analyses. Fourier analysis gives the peak periods of the waves whereas wavelet analysis gives the evolution of tsunami energy over time and frequency domains; this is why wavelet analysis is also known as frequency-time analysis. A combination of wavelet and Fourier analyses has been reported fruitful in detecting tsunami governing periods (RABINOVICH and THOMSON 2007; HEIDARZADEH and SATAKE 2013b). The waveform length is 9 and 10 h for Karachi and Mumbai, respectively. Wavelet analysis is performed using *Morlet* mother function with a wavenumber of 6 and a wavelet scale width of 0.10 (TORRENCE and COMPO 1998). For Fourier analysis, we apply two different methods: 1) the global wavelet spectrum provided by wavelet analysis, and 2) Welch's averaged modified-periodogram by considering Hamming window and overlaps (WELCH 1967) for which we use the Matlab command *pwelch* (MATHWORKS 2014).

4.2. Tsunami forward modeling

Tsunami forward modeling is a trial-and-error procedure to optimize tsunami source parameters (e.g., HEIDARZADEH and SATAKE 2013b; TAKAHASHI et al. 1995; TINTI et al. 1999). For tsunami modeling, we use a bathymetry grid of 925 m × 925 m based on the 30

arc-second GEBCO-08 bathymetric data (IOC et al. 2003). Such a grid size is appropriate since the tsunami wavelengths are estimated to be around 200-300 km from the earthquake magnitude. In our grid system, the Karachi tide gauge is located at 66.985 °E and 24.767 °N at the water depth of 7 m and the Mumbai station is located at 72.751 °E and 18.906 °N at the water depth of 11 m. The numerical model TUNAMI is used here (GOTO et al. 1997; YALCINER et al. 2004) which solves non-linear shallow water equations using leap frog scheme on a staggered grid system. We apply analytical formulas by OKADA (1985) to calculate seafloor and coastal deformation due to the submarine faulting using earthquake source parameters. The calculated deformation was used as initial condition of tsunami simulation as well as comparison with the co-seismic deformation reported by PAGE et al. (1979). The simulations were performed for a total time of 6-7 h with a time step of 2.0 s. Tsunami inundation on dry land is not included, hence a reflective boundary condition was imposed on the shoreline.

4.3. Tsunami waveform inversion

Optimization of the tsunami source is also performed by considering a heterogeneous slip distribution on the fault plane. In this context, the fault plane is divided into a number of sub-faults, and the amount of slip on each sub-fault is calculated by minimizing the difference between observed and simulated waveforms in Karachi and Mumbai. First, tsunami waveforms due to a unit slip on each sub-fault are calculated at the two locations. We call these waveforms as Green's functions $g_{ij}(t)$ where $i = 1, 2, \ldots, M$ refers to observation stations and $j = 1, 2, \ldots, N$ refers to sub-faults. Here, $M (= 2)$ and $N (= 4)$ are the total number of observation locations and sub-faults, respectively. Then, it is assumed that the final simulated tsunami waveform in a particular location number k [$i.e., Z_k(t)$] is a linear combination of Green's functions at that

location [$g_{kj}(t)$] with different coefficients (C_j), as indicated below (SATAKE 1987; SATAKE et al. 2013):

$$Z_k(t) = \sum_{j=1}^{N} g_{kj}(t)\, C_j \tag{1}$$

where coefficients C_j in Eq. (1) need to be calculated in a way that they minimize the difference between observed waveform at location number k [$i.e., \eta_k(t)$] and simulated ones [$i.e., Z_k(t)$]. Because the Green's functions are calculated for a unit amount of slip, the coefficients C_j are the final slip amounts on each sub-fault, and are calculated by taking into account all available observations as follows:

$$min: \sum_{i=1}^{M} \sum_{j=1}^{N} \left\| g_{ij}(t)\, C_j - \eta_i(t) \right\|_2^2 \tag{2}$$

where $C_j \geq 0$ and $\|.\|_2$ denotes the Euclidean norm (KREYSZIG 2010). For performing this optimization, only the first waves in each location are used. For solving Eq. (2), we apply the non-negative least-square solver "*lsqnonneg*" from the optimization toolbox of the Matlab software (MATHWORKS 2014). As two tsunami waveforms have different amplitudes, accuracy and importance, we apply different weight factors on the waveforms as described in sections 7.1 and 7.2

For regions with steep bathymetry slopes, it is more accurate to consider the effect of horizontal deformation in tsunami inversion (TANIOKA and SATAKE 1996). However, it is well known that the Makran region is characterized with gentle slopes and is the only subduction zone in the world that does not have a trench (HEIDARZADEH et al. 2008a). Hence, we do not consider such an effect in our inversion.

5. Results of spectral analysis and the governing periods

The observed tide gauge waveforms at Karachi and Mumbai are first analyzed to study the tsunami characteristics at these locations. The spectra shown in Fig. 3 are calculated using two different methods: Fourier analysis using Welch's method (line plots at the bottom panels)

and wavelet analyses (2D color maps and line plots to the right of them). Although the peak periods are the same in both methods, the amount of energy is different. This difference is due to the nature of Fourier and wavelet analyses; the Fourier analysis gives the power of tsunami over the entire record whereas the wavelet analysis gives the time evolution of tsunami energy. Thus, to determine the governing period of tsunami in each station, we use the results of Fourier analysis given by the Welch algorithm. Based on Fig. 3, the three peak periods are around 22-25, 40-50, and 85-90 min in both Karachi and Mumbai stations. For Karachi, the governing period is around 40-50 min whereas it is around 22-25 min at Mumbai. This difference is also evident in tsunami waveforms (Fig. 2b-d) which indicate that the first wave arriving at Mumbai is shorter in period than that arriving in Karachi. In both stations, a 90-min signal is also clear in tsunami spectra in Fig. 3. The time interval between the two wave crests recorded at Port Victoria was 21 min (Fig. 2d) indicating that this is the tsunami period at this station.

Wavelet plots in Fig. 3 show that tsunami energy is switching between the period bands of 22-25, 40-50 and 85-90 min at different times. In Karachi, most of the tsunami energy is concentrated around the period band of 85-90 min and 40-50 min throughout the waveform of 9 hours. In Mumbai, the signal with the period of around 22-25 min is stronger than the 90-min signal during the first hour after tsunami arrival; later, the 90-min signal shows more strength than the 22-min one.

Tsunami source periods are usually dictated by the water depth at the location of the source and by dimensions of the tsunami source and can be calculated using tsunami phase velocity (C) as follows:

$$C = \sqrt{gd} \tag{3}$$

$$C = \lambda/T \tag{4}$$

$$T = 2L/\sqrt{gd} \tag{5}$$

in which , λ is tsunami wavelength, g is gravitational acceleration which is 9.81 m/s^2, d is ocean water depth at the location of the tsunami source, T is tsunami period, and L is the source

length. As indicated in Eq (5), tsunami wavelength (λ) is usually twice the tsunami source length (L). Equation (5) indicates that the shallower the water depth at the tsunami source, the longer the period of the resulting tsunami. For example, by assuming an arbitrary source length of 100 km for a particular tsunami occurring at two different water depths of 100 and 2000 m, the periods of the resulting tsunamis will be 106 and 24 min, respectively. The peak periods of the 1945 Makran tsunami, distributed in a wide range of 22-90 min, may indicate that the tsunami source is possibly extended from near shore shallow waters of around 100 m to offshore deep waters of around 2000-3000 m.

6. Results of tsunami forward modeling

6.1. Simulations from previously-proposed source models

We compare the previously-proposed source models in terms of their agreements between observed and simulated tsunami waveforms and their capabilities in reproduction of 1-3 m of uplift in Ormara (Fig. 4a). None of the source models can produce uplift in Ormara (Fig. 4a/top). The observed tsunami waveforms (Fig. 2b-c) show that the period of the first wave arriving in Karachi is 85-90 min and longer than that in Mumbai (22-25 min). Figure 4a/bottom indicates that the source HDZ-2009 is the only one capable of reproducing a first 22-min signal in Mumbai (Fig. 4a). Other models failed to reproduce the first 22-min signal in Mumbai. In terms of the polarity of the first wave (i.e., first elevation or depression wave), all of the source models give the same results as the observations. While the wave heights resulted from the three source models of NET-2011, HDZ-2008 and HDZ-2009 are almost in the same order, the source JWL-2009 yields wave heights up to five times larger than others.

According to Fig. 4a/bottom, the source HDZ-2009 presents a relatively better agreement between observed and simulated waveforms. The simulated arrival times and periods of the first waves at Karachi and Mumbai are close to the observed waveforms, although the

simulated wave heights are smaller than the observed ones in Mumbai. In addition, spectral analysis shows that the computed spectrum at Mumbai resulting from the source HDZ-2009 is the only one showing three peak periods at around 22-25, 40-50 and 85-90 min (Fig. 4b). The simulated spectra using the source HDZ-2009 (Fig. 4b) are almost the same as the observed spectra at both stations. Therefore, we may conclude that the source by HDZ-2009 is more likely to represent the true source of the 1945 Makran tsunami. However, this source also fails in reproducing uplift in Ormara similar to other source models. From the locations of the fault models (Table 1 and Fig. 2a), it may be concluded that the tsunami source is more likely to be located in offshore deep waters; around the latitude of 24.5°E where water depth is about 2000 m. This conclusion agrees with the results of spectral analysis presented in the previous section. The source by HDZ-2009 will be the basis for further attempts to reach a better agreement between observations and simulations.

6.2. Sensitivity analysis of the source model

The target criteria for reaching an optimum source are: (1) agreement between observed and simulated waveforms, (2) generation of subsidence in Pasni and about 1-3 m of uplift in Ormara, and (3) keeping the moment magnitude of the earthquake in the magnitude range of 8.0-8.3 as reported in the literature (e.g., BYRNE et al. 1992; RICHTER, 1958; DUDA, 1965). Table 2 and Fig. 5a present the details of 26 source scenarios which examine the effects of length/location, strike angle, width, depth, rake angle, dip angle, and slip on the tsunami waveforms in Karachi and Mumbai. Since the source HDZ-2009 produced a better agreement between observed and simulated waveforms (Fig. 4a,b), we change the source parameters of HDZ-2009 to improve it through sensitivity analysis. The source parameters of HDZ-2009 are mostly based on the seismic inversion study by BYRNE et al. (1992), which are associated with some errors. Therefore, we consider an error range for each parameter and study the sensitivity of the simulated tsunami waveforms to such error ranges. All scenarios are extended to Ormara

in order to reproduce an uplift of around 1-3 m there (Table 2 and Fig. 5a-d). Results of sensitivity analysis are shown in Fig. 5e whose main findings are:

I. Effect of length/location: by increasing the source length along the strike with the fixed eastern end, the tsunami governing period decreases while the amplitude of the first wave increases. This is because tsunami source in shallower waters generate relatively longer periods compared to deeper waters, as explained in Section 5.Two scenarios of L-200 and L-237 yield waveforms similar to the observed at Mumbai, while none of the models can reproduce the observed amplitude at Karachi (Fig. 5e); hence we choose a source length of 220 km. According to this test, the tsunami source needs to be extended into the water depth of around 3000 m in order to be able to reproduce the relatively short period of around 22 min in Mumbai.

II. Effect of strike angle: the two strike angles of $230°$ and $245°$ result in a better agreement with observations in Mumbai in terms of the arrival time and period (Fig. 5e). The source scenario ST-260, located in shallow water (Fig. 5a), produces poor result (Fig. 5e). To base our choice of strike angle on an objective base, we choose the strike angle of $246°$ determined by inversion of seismic body waves (BYRNE et al. 1992) which is close to the values suggested by our sensitivity analysis.

III. Effect of source width: by increasing fault width from 40 to 100 km, the tsunami period remains almost the same, wave amplitude increases, and the difference between the amplitudes of the first and the second waves in Mumbai increases. Although the elevation of the first wave generated by scenario W-100 is close to the observations, the following depression does not match well with the observations indicating that a width of around 100 km is not appropriate. A source width of 50-70 km seems appropriate.

IV. Effect of the upper depth of the fault: no significant effect can be seen on the simulated waveforms by changing the fault depth. However, by decreasing the top depth of the fault from 37 to 17 km, the difference between the amplitudes of the first and the second waves in Mumbai decreases. Two scenarios of h-30 and h-37 seem more appropriate (Fig. 5e).

14

We choose a depth of 27 km for the top of the fault which is among the seismic parameters of the 1945 earthquake determined by inversion of seismic body waves (BYRNE et al. 1992).

V.   Effect of rake and dip angles: almost no effect can be seen on the simulated waveforms by changing the rake and dip angles (Fig. 5e). We apply the rake and dip angles of 89° and 7° calculated by BYRNE et al. (1992) for this earthquake.

VI.   Effect of slip: according to Fig. 5e, a slip of around 9-11 m is necessary to reproduce the observed amplitude in Mumbai. However, the simulated tsunami amplitudes from such scenarios are four times larger than the observed ones in Karachi.

Figure 5e shows that the simulated waveforms resulting from some of the source scenarios listed in Table 2 are similar to the observed ones. Out of the 26 different source scenarios listed in Table 2, we choose the best source parameters and list them at the last row of Table 2. A few other simulations were done to reach this best source. The results of tsunami simulations due to these best source parameters are shown in Fig. 5e/bottom. Although the agreement between observed and simulated waveform is good for the Mumbai waveform, the simulated waveform in Karachi is much larger than the observed one. Using the source parameters obtained from the sensitivity analysis, we perform an inversion analysis to reach a better agreement between observations and simulations.

7. A variable slip model

7.1. Tsunami waveform inversion

The sensitivity analysis performed in the previous section paves the ground for performing this inversion analysis through giving information about the seismic parameters of the tsunamigenic fault and its extension. We divided the entire fault into four sub-faults of A-D

(Fig. 6a) each having a dimension of 55 km (length) × 70 km (width). The tsunami Green's

function (g_{ij}) from each sub-fault (Fig. 6c) were calculated using fault parameters of strike:

246º, rake: 89º, dip: 7º, upper depth of the fault: 27 km, and slip: 1 m. The two waveforms at

Karachi and Mumbai are indicated by i as 1 and 2, respectively. The Green's functions reveal

useful information about tsunami behavior. For example, the Green's functions at Mumbai

originating from the sub-fault in offshore deep waters (i.e., g_{2A}) contain relatively shorter

periods compared to that originating from sub-fault in near shore shallow water (i.e., g_{2D}). To

reproduce the first short period of 22 min in Mumbai, we need contribution from sub-faults A or

B. In other words, if a source model lacks these offshore deep water slips (e.g., HDZ-2008 in

Fig. 4a), it will not be able to reproduce the 22-min observed signal in Mumbai.

The results of waveform inversion for three different cases are shown in Fig. 6c-e. The

first case uses only the Karachi waveform, the second case uses only the Mumbai waveform,

and the third case uses the waveforms at both stations. In the first case, the simulated waveform

at Karachi is similar to the observed one, but the simulated waveform at Mumbai is much

smaller than the observed one (Fig. 6c). The slip distribution on each sub-fault indicates that

sub-faults A and B have the same slip (1.5 m) while sub-fault D has a slip of 3.1 m. In the

second case, the agreement between observation and simulation is better for Mumbai than for

Karachi (Fig. 6d). The slip on sub-fault A is much larger (13.6 m) than the previous case, while

the slip on sub-fault D stays the same. These cases indicate that it is hard to satisfy the two

observed waveforms simultaneously by waveform inversion. The result of the third case, an

inversion using both waveforms, is shown in Fig. 6e which seems to be a median solution

between the previous two cases (Figs. 6c and 6d). The slip on sub-fault A becomes 8.3 m. The

slip distribution and seafloor deformation from this solution are shown in Fig. 6a and tsunami

simulation using such a source results in waveforms shown in Fig. 6f. While the agreement

between simulation and observation is acceptable for Karachi, it is poor for Mumbai (Fig. 6f).

However, the simulated and observed spectra agree well. We note that, for spectral analysis,

usually the peak periods are important and the absolute amounts of spectral energy are not important as they strongly depend on factors such as the length of the time series and sampling intervals. To finalize the tsunami source, we need to reach a compromise between the two observed waveforms in Mumbai and Karachi. In the next section, we finalize the source by weighting the two tsunami waveforms.

7.2. An optimum tsunami source model

The inversion of tsunami waveform at both locations yielded a compromised result; the simulated waveforms are larger than the observed one at Karachi but much smaller than the observed one at Mumbai (Fig. 6f). In addition, the simulated waveform at Mumbai shows similar amplitudes of the first and the second waves whereas the observed waveform shows that the first wave is four times larger than the second one. Because only two tsunami waveforms are available, and each of them shows different results, we need to examine the weight of each tsunami waveform in the inversion. To address the first problem, we give more weight to the Mumbai waveform, as the inversion of Mumbai waveform alone yielded larger slip (13.6 m) in sub-fault A. Result of tsunami simulation from inversion of only Mumbai waveform is shown by blue waveforms in Fig. 7d. It can be seen that while the amplitude of the first wave has increased in Mumbai, the second wave also became large and much larger than the observed. The simulated waveform in Karachi is also larger than observation. We noticed that the ratio between the amplitudes of the first and the second waves in Mumbai is affected by the offshore slip (i.e., sub-faults A and B). We also note that inversion result of only Karachi waveform required the same slip amount, albeit smaller, on sub-faults A and B. Considering these, we assumed the same slip on sub-faults A and B, and performed a trial-and-error analysis using different slip amounts on sub-faults A and B to reach an optimum slip value of 10 m for both of them. The slip amounts on sub-faults C and D are the same as those obtained using the inversion of both Karachi and Mumbai waveforms (Fig. 6c). In our final source model (Fig. 7a-

c/right), the slip distribution is closer to the results of inversion for only Mumbai waveform (Fig. 7b-c/left) than that for only Karachi waveform (Fig. 6c). In fact, we weight more the Mumbai waveform over the Karachi one in our final source, although this weighting is of qualitative nature. Application of different weights in tsunami inversion was previously used by some authors (e.g., SATAKE et al. 2013; FUJII et al. 2011). This final fault gives satisfactory results for both the first and the second waves in Mumbai (Fig. 7d/red waveforms). The simulated spectra are also close to the observed ones in both Karachi and Mumbai. Although the simulated first arrival and shape of the waveform are close to the observations in Karachi, the simulated amplitudes are larger than the observed ones. The reason is that possibly the early stages of the Karachi waveform was not recorded correctly as the gauge was out of order before the tsunami arrival. In addition, amplitude of around 20 cm in Karachi seems too small because the observed coastal wave height in Karachi was 1-1.5 m during the 1945 tsunami (HEIDARZADEH et al. 2008a).

In summary, the details of our final source are presented in Table 3 and are shown in Fig. 7a-c/right and Fig. 7d/red waveforms. Based on Fig. 7, the final source extends from onshore near Ormara (Pakistan) to offshore at water depth of more than 3000 m; in agreement with the results of our spectral analysis in Section 5.

8. Discussions

8.1. The veracity of the co-seismic uplift and seismological data

We extended the tsunami source along the fault strike up to Ormara coast following the report of co-seismic uplift in Ormara by PAGE et al. (1979), but the final calculated slip amount on the near-shore sub-fault (D) is based on the tide gauge records. Inversion of observed tide gauge records in Karachi alone, Mumbai alone, and both waveforms resulted in slip amounts of 3.1, 3.1, and 4.3 m, respectively, for sub-fault D (Fig. 6c-e). As the slip on sub-fault D has been

calculated independently from coastal deformation data, it can be used to examine the accuracy of the co-seismic uplift of 1-3 m in Ormara reported by PAGE et al. (1979). Our final fault model has a slip of 4.3 m on sub-fault D which produces a co-seismic uplift of around 1 m in Ormara (Table 3 and Fig. 7c/right). This uplift is in the reported range (1-3 m) of the co-seismic uplift by PAGE et al. (1979). Our proposed source yields a moment magnitude of around *Mw*8.3 for the earthquake (Table 3) which is the maximum value of magnitude range (8.0-8.3) reported in the literature for the 27 November 1945 earthquake (BYRNE et al. 1992; RICHTER 1958; DUDA 1965).

8.2. Near-field observations of the 1945 Makran tsunami

A runup height of 12-15 m was reported in the near-field due to the Makran tsunami of November 1945 (PENDSE 1946). However, our proposed source (Table 3) generates maximum onshore wave amplitude of around 5-6 m in the near-field (Fig. 7a) which is an approximation of tsunami runup. It was not the aim of this study to explain all of the observations other than the tsunami waveforms on tide gauges and co-seismic deformation data. Figure 2a shows that the two available tide gauge stations are located far from the source on a wide continental shelf which is an extended shallow water region. Therefore, it seems unlikely that any waves generated by local phenomena such as submarine landslides could reach them. We thus expect to receive only waves generated by the seismic source in the two examined stations as it was the case for the waves recorded on the Japan coast due to the 1998 Papua-New-Guinea tsunami (SATAKE and TANIOKA 2003). In fact, our modeling using the two available tsunami waveforms explains mainly the tectonic source of the Makran tsunami of 1945. Separate studies are needed to explain the near-field observations. It has previously been speculated that the extreme runup height of 12-15 m was the result of a possible submarine landslide or a splay fault branching from the plate boundary (e.g., HEIDARZADEH et al., 2008a).

8.3. Our source model in comparison to other studies

As discussed in Section 1, some source models have been used by other authors for the Makran tsunami of 1945 (Table 1 and Fig. 4a). Our source model is different from others in several ways: 1) our model has a heterogeneous slip distribution whereas other sources have a uniform slip, 2) our model is extended to deep water with the water depth of around 3000 m while most of the other sources lack such offshore slip, and 3) our source model also extends to near coast so that it produces an uplift of around 1 m in Ormara whereas all other sources generate no uplift there. Our source model implies a moment magnitude of Mw 8.3 (Table 3) which is larger than that of the source HDZ-2009 (Table 1) but smaller than the source HDZ-2008. Despite these differences, the maximum coastal wave height produced by our source (Fig. 7a) is close to those of the sources HDZ-2008 (Fig. 6 in HEIDARZADEH et al. 2008a) and HDZ-2009 (Fig. 6 in HEIDARZADEH et al. 2009a). In all cases, the maximum coastal wave amplitude in the near field is 4-6 m.

9. Conclusions

Spectral analysis, tsunami forward modeling as well as tsunami inversion analysis were employed to constrain the source of the Makran tsunami of November 1945 using recently-available tsunami waveforms recorded on tide gauges and co-seismic deformation data. Main findings are:

1- The tsunami peak periods were 22-25, 40-50, and 85-90 min. In Karachi, the governing period was 40-50 min whereas it was around 22 min in Mumbai. In Port Victoria (Seychelles), the period of the first wave was 21 min. Distribution of tsunami energy in a wide period band of 22-90 min may indicate that the tsunami

20

source fault was possibly lying from near shore shallow waters of around 100 m to offshore deep waters of around 3000 m.

2- Tsunami modeling using previously-published source models showed that only a source located offshore at the water depth of around 2000-3000 m is able to reproduce the observed 22-min signal in Mumbai. However, all of the previously-published sources fail in reproduction of 1-3 m of uplift in Ormara.

3- Sensitivity analysis gives us the two end points of the earthquake rupture zone: in one hand, the seafloor deformation caused by the earthquake needs to be located in the offshore deep water around the water depth of 2000-3000 m in order to reproduce the first 22-min signal in Mumbai, and on the other hand, the deformation zone needs to be extended up to Ormara in order to reproduce the observed 1-3 m of co-seismic uplift there.

4- Based on the inversion of the available tsunami waveforms recorded on tide gauges at Mumbai and Karachi, we propose a 4-segment fault with varying slip amounts as the tsunami source. This source includes a slip of 4.3 m onshore near Ormara (Pakistan) and a slip of 10 m offshore at the water depth of around 3000 m. The total length of the fault is 220 km and average slip is 6.1 m. Other source parameters include width: 70 km, southeast corner of the fault plane: 64.941°E and 24.923°N, top depth: 27 km, dip angle: 7°, slip angle: 89°, and strike angle: 246°. This source: first, reproduces fairly well the observed waveforms in Mumbai and Karachi; second, produces ~1 m of uplift in Ormara and ~1 m of subsidence in Pasni; and third, gives a magnitude of 8.3 for the earthquake which is in the acceptable range.

5- The computed 1 m of uplift in Ormara is in the range of the reported uplift of 1-3 m in the literature.

6- As the tide gauge stations were located in the far-field inside an extended shallow region, our proposed source explains mainly the tectonic source of the tsunami.

Acknowledgement

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Tables:

Table 1. Fault parameters used for modeling of the Makran tsunami of 27 November 1945 in previous studies

Source name	Mw[5]	Location[6]		Water depth (m)	Length (km)	Width (km)	Slip (m)	Depth[7] (km)	Dip (deg)	Rake (deg)	Strike (deg)
		Lon (°E)	Lat (°N)								
HDZ-2008[1]	8.4	64.01	25.06	50	200	100	7.3	20	5.5	90	240
JWL-2009[2]	8.6	63.90	24.05	2000	200	100	15	30	15	90	270
HDZ-2009[3]	8.1	64.17	24.45	2000	130	70	6.6	27	7	89	246
NET-2011[4]	8.2	64.59	24.87	15	100	100	7	15	7	89	246

[1]HEIDARZADEH et al. (2008a); [2]JAISWAL et al. (2009); [3]HEIDARZADEH et al. (2009a); [4]NEETU et al. (2011); [5]Moment magnitude which is calculated based on the seismic moment of the source fault; these values may differ from magnitude values reported by the authors in the respective articles; [6]The southeast corner of the fault plane; [7]Upper depth of the fault.

Table 2. Different source scenarios used for sensitivity analysis. Numbers with bold characters indicate parameters that change in every set of analyses

| | Scenario name | Location[1] | | Length (km) | Width (km) | Slip (m) | Depth[2] (km) | Strike (deg) | Rake (deg) | Dip (deg) | Vertical crustal deformation | | Mw^3 |
		Lon. (°E)	Lat. (°N)								Ormara	Pasni	
Length/location	L-237	65.06	24.87	**237**	70	7.5	27	246	89	7.0	+1.7	-1.5	8.35
	L-200	65.06	24.87	**200**	70	7.5	27	246	89	7.0	+1.7	-1.5	8.30
	L-142	65.06	24.87	**142**	70	7.5	27	246	89	7.0	+1.7	-0.9	8.20
	L-120	64.97	25.07	**120**	70	7.5	27	246	89	7.0	+2.0	-0.2	8.15
Strike	ST-230	64.71	24.93	180	60	8.0	27	**230**	89	7.0	+1.5	-1.0	8.24
	ST-245	64.71	24.93	180	60	8.0	27	**245**	89	7.0	+1.5	-1.5	8.24
	ST-260	64.71	24.93	180	60	8.0	27	**260**	89	7.0	+1.6	+0.6	8.24
Width	W-40	64.72	25.04	204	**40**	8.0	27	235	89	7.0	+1.2	-0.7	8.16
	W-60	64.77	24.98	204	**60**	8.0	27	235	89	7.0	+1.5	-1.5	8.28
	W-80	64.82	24.89	204	**80**	8.0	27	235	89	7.0	+1.6	-1.6	8.36
	W-100	64.86	24.81	204	**100**	8.0	27	235	89	7.0	+1.7	-0.7	8.43
Depth	h-17	64.79	25.02	204	50	8.0	**17**	235	89	7.0	+1.7	-0.8	8.23
	h-24	64.79	25.02	204	50	8.0	**24**	235	89	7.0	+1.3	-1.0	8.23
	h-30	64.79	25.02	204	50	8.0	**30**	235	89	7.0	+1.3	-1.1	8.23
	h-37	64.79	25.02	204	50	8.0	**37**	235	89	7.0	+1.1	-1.1	8.23
Rake	R-70	64.79	25.02	204	50	8.0	17	235	**70**	7.0	+2.0	-0.8	8.23
	R-83	64.79	25.02	204	50	8.0	17	235	**83**	7.0	+1.9	-0.9	8.23
	R-96	64.79	25.02	204	50	8.0	17	235	**96**	7.0	+1.7	-0.9	8.23
	R-110	64.79	25.02	204	50	8.0	17	235	**110**	7.0	+1.2	-0.8	8.23
Dip	D-5	64.79	25.02	204	50	8.0	17	235	89	**5.0**	+1.7	-0.8	8.23
	D-7	64.79	25.02	204	50	8.0	17	235	89	**7.0**	+1.7	-0.8	8.23
	D-9	64.79	25.02	204	50	8.0	17	235	89	**9.0**	+1.7	-0.7	8.23
Slip	S-4	64.79	25.02	204	50	**4.0**	17	235	89	7.0	+0.9	-0.4	8.03
	S-6	64.79	25.02	204	50	**6.0**	17	235	89	7.0	+1.4	-0.6	8.14
	S-9	64.79	25.02	204	50	**9.0**	17	235	89	7.0	+2.0	-1.0	8.26
	S-11	64.79	25.02	204	50	**11.0**	17	235	89	7.0	+2.5	-1.2	8.32
	Best	64.79	25.02	220	50	9.0	27	246	89	7.0	+1.8	-1.0	8.28

[1] The southeast corner of the fault plane; [2]Upper depth of the fault; [3]Moment magnitude calculated by assuming the rigidity of the earth as 3×10^{11} dyn/cm^2.

Table 3. A summary of the final source parameters proposed for the Makran tsunami of November 1945 based on the results of this study

Segment Name	Location* Lon.[1] (°E)	Location* Lat.[2] (°N)	L^3 (km)	W^4 (km)	Slip (m)	Depth[5] (km)	Strike (deg)	Rake (deg)	Dip (deg)	Vertical crustal deformation Ormara	Vertical crustal deformation Pasni	M_0^6 (dyne-cm)	Mw
A	63.48	24.27	55	70	10.0	27	246	89	7			1.16×10^{28}	
B	63.97	24.49	55	70	10.0	27	246	89	7			1.16×10^{28}	
C	64.46	24.71	55	70	0.0	27	246	89	7			0.0	
D	64.95	24.92	55	70	4.3	27	246	89	7			4.97×10^{27}	
Total/average			220	70	6.1	27	246	89	7	+0.9	-1.0	2.81×10^{28}	8.27

[1]Longitude; [2]Latitude; [3]Length; [4]Width; [5]Upper depth of the fault; [6]Seismic moment calculated by assuming the rigidity of the earth as 3×10^{11} dyn/cm²; *The southeast corner of the fault plane.

Figure Captions:

Fig. 1. General tectonic setting of the northwestern Indian Ocean and the epicenter of the Makran earthquake of 27 November 1945 (asterisk) according to BYRNE et al. (1992). The yellow rectangle shows an approximation of the tsunami source. Color map shows the distribution of the maximum heights of the 1945 Makran tsunami as calculated by HEIDARZADEH et al. (2008a). Contours with numbers are tsunami travel times in minutes. Dashed lines represent plate boundaries. SZ stands for subduction zone.

Fig. 2. (a): A perspective view of the bathymetry of the northwestern Indian Ocean with projected faults proposed for the 1945 Makran tsunami in previous studies. Asterisk shows the epicenter of the earthquake. The blue, brown, yellow and purple dashed-rectangles are approximations of the tsunami source previously proposed by HEIDARZADEH et al. (2008a), JAISWAL et al. (2009), HEIDARZADEH et al. (2009a), and NEETU et al. (2011), respectively. (b)-(c): Tide gauge records of the Makran tsunami of November 1945 in Karachi and Mumbai, respectively. The purple-dashed line represents the earthquake origin time. (d): The descriptive sea level observation of the 1945 Makran tsunami in Port Victoria, Seychelles as reported by BEER and STAGG (1946). (e): Co-seismic deformation as reported by PAGE et al. (1979).

Fig. 3. Results of spectral analyses for the two observed tide gauge records of the Makran tsunami of November 1945. The color plots show the results of wavelet analysis in $0.01 \times \text{Log}_2$ (spectral energy). The small panels to the right of wavelet plots are the global wavelet spectra.

The purple- and white-dashed lines represent the earthquake origin time and tsunami arrival times, respectively. Bottom panels are tsunami spectra calculated using Welch algorithm.

Fig. 4. (a): Tsunami simulations for previously-proposed source models for the 1945 Makran tsunami. Top row shows the initial seafloor deformation produced by different source models. Snapshots in middle row are based on the simulations using the source HDZ-2009. Two bottom panels are the comparison of observed (dashed lines) and simulated (colored solid lines) waveforms at Karachi and Mumbai. (b): Results of wavelet analyses for simulated waves from different source models. The small panels to the right of each wavelet plot are the global wavelet spectra (GWS). Vertical-dashed line represents the earthquake origin time. The color bar shows $0.01 \times \text{Log}_2$ (spectral energy). The dashed and solid lines in tsunami spectra represent observed and simulated spectra, respectively. The numbers inside the spectral plots show the factors used to normalize the amount of spectral energy for simulated waveforms in order to ease the comparison between observed and simulated spectra. HDZ-2008, HDZ-2009, JWL-2009, and NET-2011 represent HEIDARZADEH et al. (2008a), HEIDARZADEH et al. (2009a), JAISWAL et al. (2009), and NEETU et al. (2011), respectively.

Fig. 5. (a): Projection of different source scenarios used for sensitivity analysis according to Table 2. (b-c): Seafloor deformation due to selected source scenarios listed in Table 2. (d): Seafloor deformation due to the scenario "Best" in Table 2 which is the outcome of the sensitivity analysis. (e): Simulated tsunami waveforms in Karachi and Mumbai (solid-colored lines) resulting from different source scenarios listed in Table 2 in comparison to the observed waveforms (dashed-black lines).

Fig. 6. Results of tsunami waveform inversion. (a): Locations of four sub-faults. The numbers on sub-faults are slip amounts obtained from the inversion of both Mumbai and Karachi waveforms. (b): Seafloor deformation due to the inversion result. (c): Results of inversion study by using only Karachi tide gauge record. The coefficients C_A to C_D represent the amount of slips on sub-faults A to D, respectively. (d): Results of inversion study by using only Mumbai tide gauge record. (e): Results of inversion study by using both tide gauges. (f): Results of tsunami simulations, both waveforms and spectra, using the solution shown in (e).

Fig. 7. Distribution of coastal wave height (a), slip distribution (b), seafloor deformation (c) and simulated tsunami waveforms and spectra in Karachi and Mumbai (d) from the inversion result of Mumbai waveform alone (left) and our final proposed source fault in Table 3 (right). MO and OBS stand for Mumbai Only and Observations, respectively.