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Methodological analysis for the tsunami warning system in the Makran Sea

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Abstract

The present study is an attempt to investigate a technique used for tsunami warning in advance. In this study, the available data on the physical parameters of seawater in the Arabian Sea and the Oman Sea were analyzed. The potential spatial and temporal variability of the Sound Fixing and Ranging (SOFAR) resulting from various phenomena such as wind, surface currents, interior currents, sed i mentation were assessed. Therefore, we investigated the possibility of seismic noise transmission in SOFAR channel. Finally, the sound signal's travel time was calculated and compared with the arrival time of a potential tsunami. The methodology was the identification of a sloping SOFAR channel in the study area, calculation of the travel time of underwater earthquake-induced sound in the channel, and comparison of the results with the time of the occurrence of a real tsunami in the region. The sound travel time is one seventh of the travel time of an earthquake-generated tsunami.

Keywords: Tsunami; Makran Sea; Arabian Sea; DART system; SOFAR.

1. Introduction

The Indian Ocean is one of the major earthquake prone and tsunamigenic marine zones. The Oman Sea, which covers some thrust faults, is also of particular importance in terms of underwater seismicity and tsunamigenicity. The long coastlines in the south of Iran, especially near the Makran Sea and Indian Ocean, are at considerable risk of tsunami. In the case of faults in these areas actively contribute to underwater earthquakes; they will be able to create tsunami waves that threaten all facilities built on the shores of the Makran Sea causing considerable financial and life losses. The extent of losses may vary depending on the tsunami wave's power, the type of shorelines as well as the type of structures built in this region.

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Therefore, prevention and mitigation of the damages caused by such tsunami waves, calls for designing, implementing and installing the systems that are capable of providing timely warnings and evacuation of the areas to reduce potential of life losses. However, considering the probability of such incidents in the shores of the Makran Sea, it is possible to formulate and provide users with specific guidelines. These guidelines show structure types, and their distance to the marine region. There are different studies about tsunami warning systems in different tsunami- p rone parts of the world. These studies are mainly based on the underwater seismology and sea water level determination. The inability to predict the time of occurrence, magnitude, and the direction of the dominant wave are among the shortcomings of these systems.

The present study is an attempt to investigate a technique which actually evaluates the applicability of submarine SOFAR channel potentials for transmission of earthquake-induced sound signals. Regardless of their advantages, the systems based on communication of recorded seismic information are associated with some disadvantages, including high maintenance costs, equipment wearing, and wave interference. The sound channel is a natural underwater waveguide formed by vertical sound velocity profile resulting from the natural physical properties of sea water and its surface-depth distribution, which is capable of transmitting sound across long distances such that the sound signals available around the sound emitting source can be detected by suitable receivers. In order to accomplish the present study, first, it is necessary to study the tsunamigenicity potentials in the Indian Ocean and the Makran Sea and then assess the potential of these marine areas to have underwater sound channels. The results of these studies can provide us the knowledge of exploiting the sound channel potentials in receiving earthquake-induced sound waves and consequently prediction of the tsunami occurrence time in a specific region. Some relevant studies carried out in this field are as follows:

- Shah Hosseini *et al*. (2011): Boulders as Evidence for High-Energy Waves on the Iranian Coast of Makran.
- Mokhtari (2011): Tsunami in Makran Region and Its Effect on the Persian Gulf.
- Heidarzadeh and Kijko (2011): A Probabilistic Tsunami Hazard Assessment for the Makran Subduction Zone at the Northwestern Indian Ocean
- Titov *et al*. (2005): The Timely Prediction of a Tsunami
- Berberian (1994): The First Earthquake Catalog of Iran
- Page *et al*.(1979): Evidence for the Recurrence of Large Magnitude Earthquakes along the Makran Coast of Iran and Pakistan
- Pararas (2006): The Potential for Tsunami Generation along the Makran Subduction Zone in the Northern Arabian Sea

Ocean is an acoustically complex environment characterized by its heterogeneous nature. We distinguish two types of heterogeneity, 'owing to chance' and 'systematic'. Both heterogeneity types significantly affect on the sound field in the ocean. A regular change in sound speed with depth will lead to the formation of underwater sound channels. Owing to chance heterogeneities also cause sound propagation and disturb the sound field.

Sound channel or SOFAR, which stands for Sound Fixing and Ranging, is a layer of seawater that might vary in thickness depending on the physical properties of water. In this layer, the sound waves propagating in the water fall into a trap due to the diffraction of the sound beams above and below this layer, and then travel across a long distance in that layer. Along the path, successive refractions may occur above and below this layer, and sound beams return to this layer again. The axis of this channel passes exactly through the point of minimum sound speed at the water column. In case the beam method is the basis for examining the volume of sound compression waves in the water, the refraction of sound beams into the channel will take place according to the Snell's law. Accordingly, the Snell law describes the refraction of sound beams in sea water with any change in density. In light and sound physics, the change in density is defined by a constant coefficient known as refraction index.

2. Materials and methods

A Tsunami happens, when the sea floor abruptly deforms and vertically is displaced the overlying water. Tectonic earthquakes are a special type of earthquake associated with deformation of the earth's crust. When such earthquakes occur under the sea, water mass is displaced from its equilibrium state. Furthermore, a tsunami occurs when destructive or convergent plate boundaries move unexpectedly. The displacement of water is due to the vertical component of movement and abrupt displacement. Movement on normal faults also causes the displacement of the seafloor, but the size of largest events of this kind is usually too small to generate a large tsunami. Tsunami in offshore areas has small amplitude (wave height) and very long wavelengths (usually several hundred kilometers). While, the typical sea waves have a wavelength of about 30 to 40 meters, which is why they generally pass unnoticed at sea, forming only a passing "hump" in the ocean and can cause a dead wave of about 300 mm on the free surface of the sea, rising rapidly when it reaches shallow areas (Figure 1 and Figure 2). Some atmospheric conditions such as tropical cyclone can also generate a storm surge referred to as meteorological tsunami, which is able to increase the water level unexpectedly in coastal areas.

2.1. Data collection and data stations

The seismic data of this zone is collected and processed according to the Dziewonski's

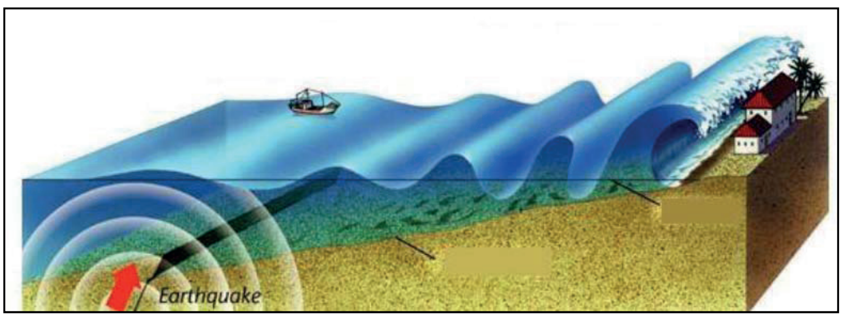

Figure 1. Tsunami wave in deep and shallow water

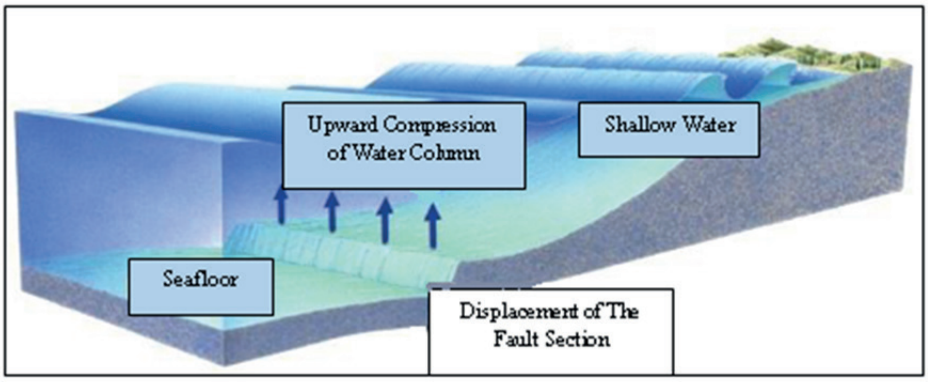

Figure 2. The arrival of tsunami waves to the coast (inio.ac.ir)

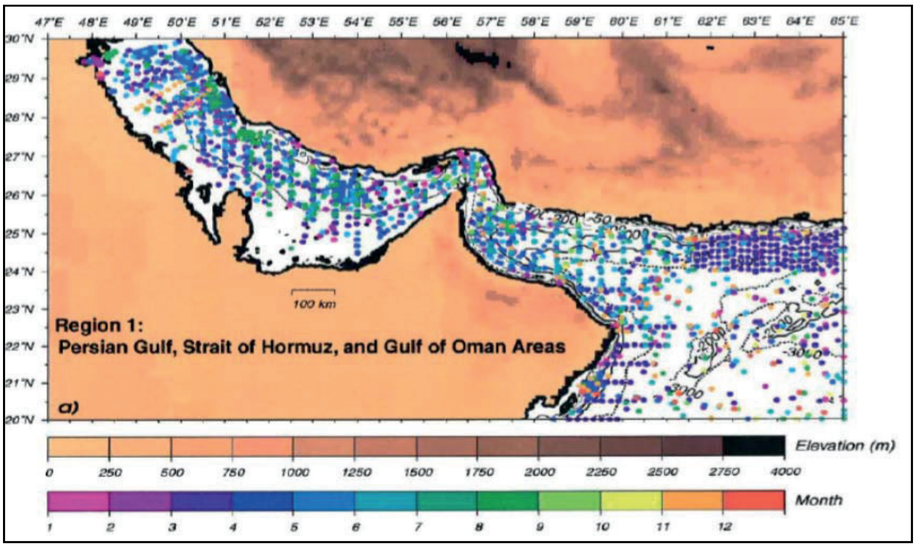

Figure 3. Geographical distribution of the data collected by the WHOI during 1923-1996

centroid-moment tensor solutions (Dziewonski *etal*.,1981) which was developed for earthquakes larger than which occurred in the area during 1977-2002. All obtained earthquakes were greater than5.8 Richter occurring in this region during 1948-1976 (Chandra, 1984). The data associated with 1923 - 1996 were also reviewed in order to cover all the data associated with the study area (Figure 3).

The profiles presented in the Figure 4 reflect the mixed layer depth and the beginning of the thermocline region that can provide the ground for proper assessment of the depth of sound channel formation in the area. These profiles show variations of salinity and temperature with depth. These two parameters affect sound speed profile and show formation of a sound channel. MATLAB software (7.0.4) and SPSS software (19) were used to draw diagrams and to analyze the data.

3. Results

When a tsunami occurs, the first wave reaches the coast and starting to growth and suddenly breaks down to generate an unexpected flood

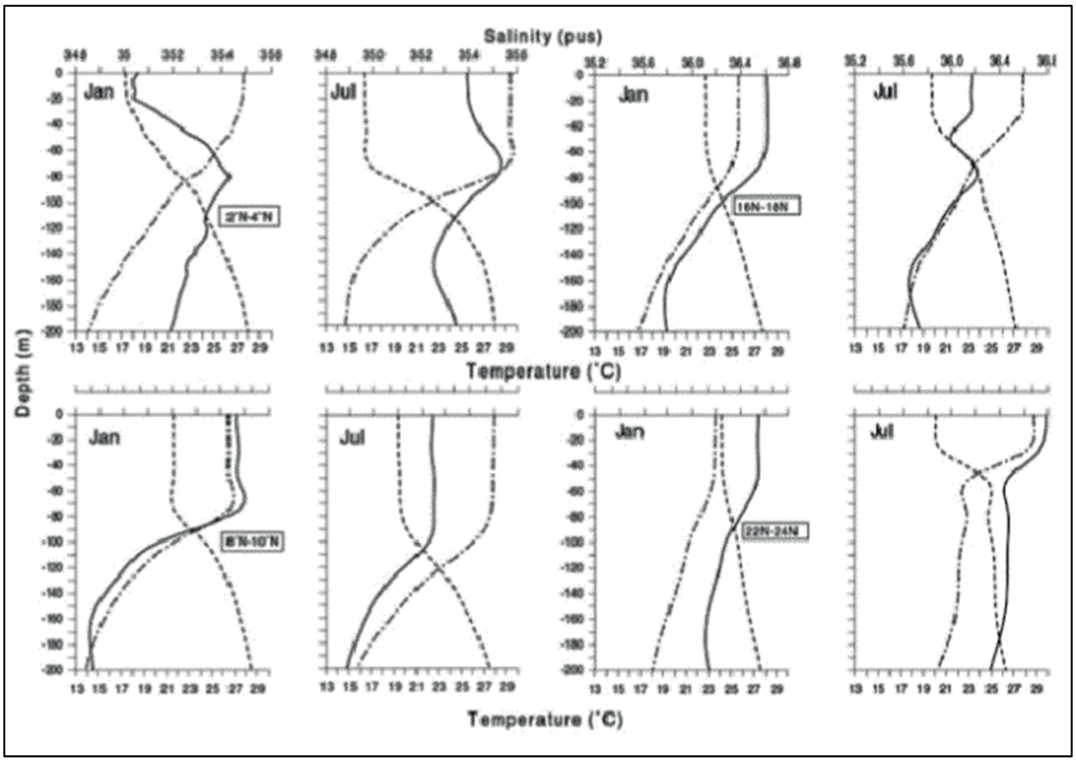

Figure 4. Vertical temperature profiles (dot-dashed line), salinity (continuous line) and sigmas (broken lines) for a change of 2 degrees along 50° east of the Arabian Sea in January (left) and July (right)

on land. When a trough arrives to the shore, a drawback will occur and a wide area submerges in water. The greater the area, the more destructive the tsunami will be. Within the next 6 minutes, the wave trough develops into a ridge, which may flood the coast and cause destruction in the coast. In the next six minutes, the wave changes from a ridge to a trough and the flood- waters recede in a second drawback. During the drawback, the coast undergoes massive destructions and the resulting debris will be swept back to the sea. The process was repeated with succeeding waves. The first scale that genuinely calculated the magnitude of a tsunami, rather than its intensity at a particular location, was the ML scale. Murty and Loomis (1980) proposed the scale based on the potential energy.

$$ML = 2(\log E - 19) \quad (1)$$

where, E is the tsunami energy in erg.

The difficulty in calculating the potential energy of a tsunami means that this scale is rarely used. Abe and Hatori (1982) introduced the tsunami magnitude scale,, which is calculated as follow:

$$M_t = a * \log(h) + b * \log(R) + D \quad (2)$$

Where h is the maximum tsunami-wave amplitude in meter, measured by a tide gauge at a distance of R from the epicenter, a, b and D are constants used to make the M_t scale match as closely as possible with the moment magnitude scale.

Changes in characteristics of a tsunami wave are on the changes in the environment. Thus, according to Green's Law, the Kajiura (1970) model is as follows:

$$\frac{A_1}{A_2} = \left(\frac{\lambda_2}{\lambda_1}\right)^{1/2} = \left[\frac{h_2}{h_1}\right]^{1/4} \quad (3)$$

where A_i and λ_i denote the amplitudes and wavelengths of a tsunami at depth of h_i in two different locations i = 1 and 2, respectively. Based on these two parameters, one can define four non dimensional quantities which are used to compare the significance of linear, nonlinear, and diffraction effects (Table 1).

The Greene's law is required when there is a tsunami in two different points (1 and 2)

$$\varepsilon_2 = \varepsilon_1 \left(\frac{h_1}{h_2}\right)^{5/4}, \delta_2 = \delta_1 \left(\frac{h_1}{h_2}\right)^{-1/2},$$

$$\gamma_2 = \gamma_1 \left(\frac{h_1}{h_2}\right)^{3/4}, Ur_2 = Ur_1 \left(\frac{h_1}{h_2}\right)^{9/4} \quad (4)$$

In fluid dynamics, Ursell number indicates the nonlinearity of long surface gravity waves on a fluid layer. Linear wave theory is applicable for long waves ($\lambda > h$) with a small Ursell number ($Ur \le \frac{32\pi^2}{3} \approx 100$). This number is represented as follows:

$$U_r = \frac{H}{h}\left(\frac{\lambda}{h}\right)^2 = \frac{H\lambda^2}{h^3} \quad (5)$$

where, H denotes the wave height and h is the depth of water in meters.

Assume a typical tsunami wave with the following characteristics: A_1=1m, h_1=3*km*, and λ_1=100*km*. In this case, Table 2 represents the corresponding dimensionless parameters.

These values show that the linear theory is applicable for defining wave behavior up to a certain depth, and we can assume a relatively mild diffraction effect for a wave that travels over very long distances. In case of short travel distances up to a few kilometers, linear shallow water equations are sufficient. As the wave approaches the coast, finite amplitude (nonlinear) effects come into play when $\varepsilon_2 \approx 10^{-1}$. According to Equation 4, this effect occurs at a depth of h_2 = 31m . Assuming a seabed steepness of 0.02, it occurs at a distance of approximately 1.5 km from the shore, which is about 1/7 of the wavelength of a tsunami with a period of 10 min.

The dimensionless parameters pertaining to the depth of 31 m are available in Table 2. The wave steepness is γ_2 = 0.0003 and the Ursell number is $Ur_2 \approx 10^4 >> 1$ indicating that the dispersion is relatively minor compared to the non-linearity, except for the front part of the wave. According to the above-mentioned points, it reasonably concluded that, in a few

Table 1. Non-dimensional quantities used to determine linear and diffraction effects

Relative Height	Wave Shallowness	Wave's Steepness	Ursell Number
$\varepsilon_i = \frac{A_i}{h_i}$	$\delta_i = \frac{h_i}{\lambda_i}$	$\gamma_i = \frac{A_i}{\lambda_i}$	$Ur_i = \frac{\varepsilon_i}{\delta_i^2}$

Table 2. Dimensional quantities of a tsunami wave

	$h_1 = 3km$	$h_2 = 31km$
ε_i	$3.3*10^{-4}$	10^{-1}
δ_i	3.03	$3*10^{-3}$
γ_i	10^{-5}	$3*10^{-4}$
Ur_i	0.367	$1.8*10^{-4}$

kilometers from the shore, there is a shift in the importance from linear effects to nonlinear effects. Therefore, the linear shallow water equations used in offshore areas should be matched to the inner solution of the nonlinear shallow-water equations at a distance from the coast of about one seventh of a tsunami wavelength. The velocity of a tsunami can be calculated using the wave speed equation at shallow water depth:

$$C=3.13\sqrt{h} \quad (6)$$

where, h is the depth of water (in meters) and c denotes velocity of the tsunami (in m/s).

Considering the movement of internal waves at the interface of layers with different densities and observing these waves at the water surface, it can be concluded that either the slope of these layers is upward, or that some phenomena such as upwelling has led to the rise of layers underneath to the water surface. But for layers like SOFAR, which are expected to be seen in long distances away from the Arabian Sea to the Oman Sea, local phenomena such as Omani upwelling cannot contribute to their upward infiltration. However, knowledge of the way physical parameters of sea water change can help us to understand that the open ocean is less affected by the boundary effect and the sound channel should be formed in deeper locations, while in the semi-closed basins, the boundary effect is more intense and the sound channel is higher. Thus, assuming that there is an interconnection between these channels, the sound channel will be like a plate with upward slope stretching from the Arabian Sea to the Oman Sea. This will make any signal generated on this panel receivable anywhere else on the same panel.

The Gulf of Oman, or the Oman Sea, that is sometimes referred to as the Makran Sea, is a strait (rather than a real gulf) connecting the Arabian Sea to the Strait of Hormuz, which then runs to the Persian Gulf. The Oman Sea generally known as a branch of the Persian Gulf, and the Makran subduction zone beneath the Arabian Sea is a place where two tectonic plates collide, and one is pushed beneath the other (Figure 5).

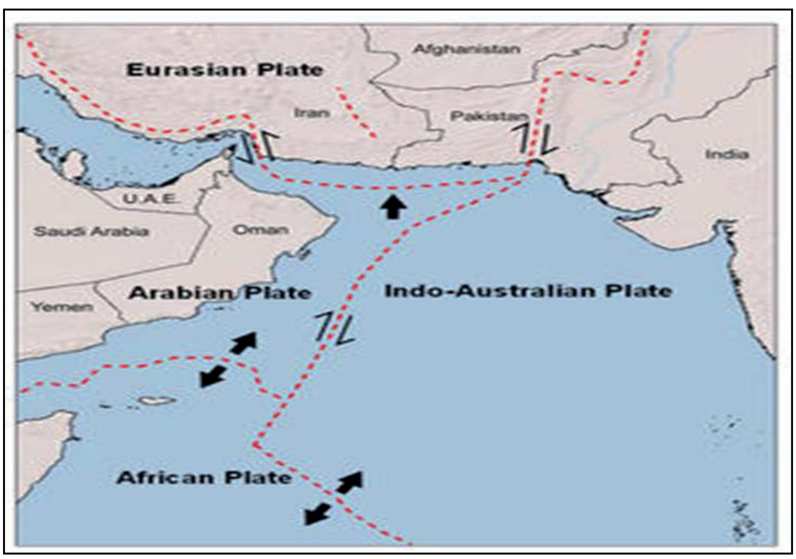

Figure 5. Subduction of the Arabian plate beneath the Eurasia plate in the Makran subduction zone

The last major earthquake in Makran subduction zone dates back to 1945. The earthquake magnitude was 1.8 in the Richter scale, giving rise to a tsunami that killed 4,000 people. The subduction zones are known for major earthquakes and volcanic eruptions, and because nine of the greatest earthquakes of the last century occurred in one of these subduction zones like Makran. These zones can also generate great tsunamis in the time of earthquake, because sudden sea floor movements result in displacement of a large amount of sea water. Recent research has shown that, unlike other subduction zones where one plate plunges down quickly, the Makran subduction zone is unusual, while the Arabian plate is actually subducted with a very low dip angle. The zone can generate earthquakes with magnitude of 2.9 Richter due to the shallow dip angle, triggering equivalent tsunamis that could be a threat for countries such as Pakistan, Iran, Oman, India, and even areas far away. Figure 6 shows the location of the Pakistan-Iran Makran subduction zone as well as the location of the earthquakes including the 1945 tsunamigenic earthquake (Mw 8.1) (the red dot on the north side of the map shows the 1947 earthquake Mw7.3) the Makran subduction zone is characterized by shallow dip of the subducting plate. Since the zone is very shallow, the model used here has created an earthquake rupture zone with a width of up to 350 kilometers, which is unusually wide, relative to most other subduction zones.

The research shows that the high sedimentary input can trigger much bigger earthquakes. If the sediments between the plates are too weak then they might not be strong enough to allow the strain between the two plates to build up, but much thicker sediments than usual are available here, which means that the deeper sediments will be more compressed and warmer. As a result, heat and pressure make the sediments stronger and the shallowest part of the subduction zone fault will have the potential of slipping during an earthquake (Figure 7). One of the greatest challenges in the Makran subduction zone is less available information

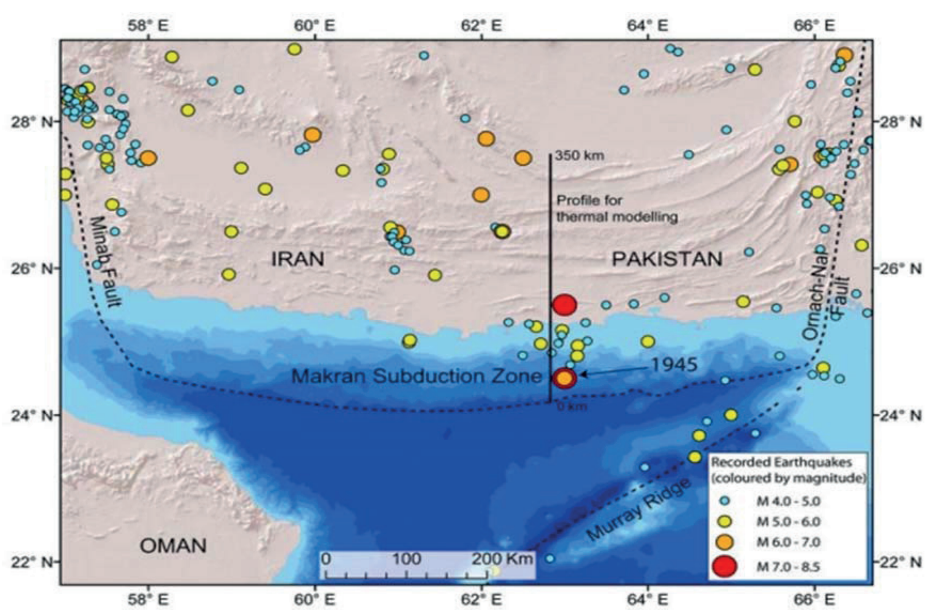

Figure 6. The Makran subduction zone and related distribution of earthquakes (phys.org)

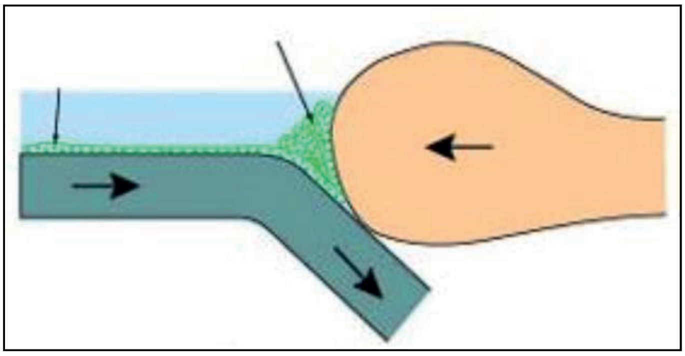

Figure 7. Accumulation and compression of sediments on the down-going Arabian plate in the Makran zone (studyblue.com)

on many of the fault characteristics in the zone, but mean values and seismic experiments taken from the model, can help us to estimate the changes in these characteristics and obtain accurate pictures of the earthquake potentials in the area (Smith *et al*., 2013).

In 2010, three tsunami buoys along with long-term maintenance services were in a region near the Makran subduction zone. These systems are part of a larger network of tsunami buoys that provide critical data on the magnitude of the tsunamis generated across the Indian Ocean.

Since the tectonic plates are prone to rupture and can generate earthquakes at temperature between 150 and 450 °C, scientists calculated the temperature of the plate collision site and performed thermal observations in the Makran subduction zone. Finally, they found that the seismic potential in this zone is much greater than what they thought before tsunamigenicity of a coastal zone generally depends on its proximity to the tsunami source. However, local conditions, such as topography and depth, should be taken into account as well. Several sources of information can be used to reconstruct past tsunamis. In most cases, historical records are a valuable asset. Historical evidence is indisputable all the time. Among all similar events, the 1945 earthquake in Makran subduction zone, which led to generation of a tsunami, is the only event recorded so far. Hence, this event has been used as a basis for modeling and could also serve as a useful resource for a tsunami warning system that has already been installed. Unfortunately, no tsunami has ever been documented on the coast of the Oman Sea. Obtaining the information on coastal vulnerability is of critical importance for development activities in the Oman Sea, Iran, and India. Pakistan's Nuclear Power Plan, on the west coast of Karachi gives us additional incentive to assess the time of tsunami recurrence in this area.

4. Discussion

The Deep-ocean Assessment and Reporting of Tsunamis (DART) system consists of two parts; a Bottom Pressure Recorder (BPR), and a surface buoy with related electronics for simultaneous data transmission. The BPR monitors water pressure with a high resolution and finally transmits data from the buoy via an acoustic modem, through the GOES Data Collection System (DCS). In normal conditions (no tsunami), the BPR transmits data on an hourly basis that each hour consisting of four 15-minute values which everyone is almost

15-seconds duration. If the water level values in two 15 seconds exceed of the values predicted by the system, the system will go into the Tsunami Response Mode, and if the water height remains undisturbed, the system will return to normal mode only after 3 hours. When a tsunami occurs, the first information about the tsunami source will be based solely on seismic data. As the tsunami wave passes through the DART system, the system sends water level information to the Tsunami Warning Center in order to get a precise estimate of the tsunami source. The analyzed data can issue watches, warnings, or evacuations. The first generation of this system was characterized by automatic detection, and reporting algorithm triggered by a threshold wave-height value. In the second generation of system, two-way communication incorporated that allows for transferring the tsunami data on demand (Figure 8). The system can measure a tsunami with the amplitude of less than 1cm in the deep ocean, using a quartz crystal pressure transducer that is sensitive to changes corresponding to less than 1mm of equivalent sea level change in the tsunami frequency band.

The open ocean is less affected by the boundary conditions and the sound channel should be formed in greater depths, while in the semi-closed basins, the boundary condition is more intense and the sound channel is higher than the one relative to the bottom. Thus, assuming that there is an interconnection between these channels, the sound channel will be like a plate with upward slope stretching from the Arabian Sea to the Oman Sea. This will make any signal

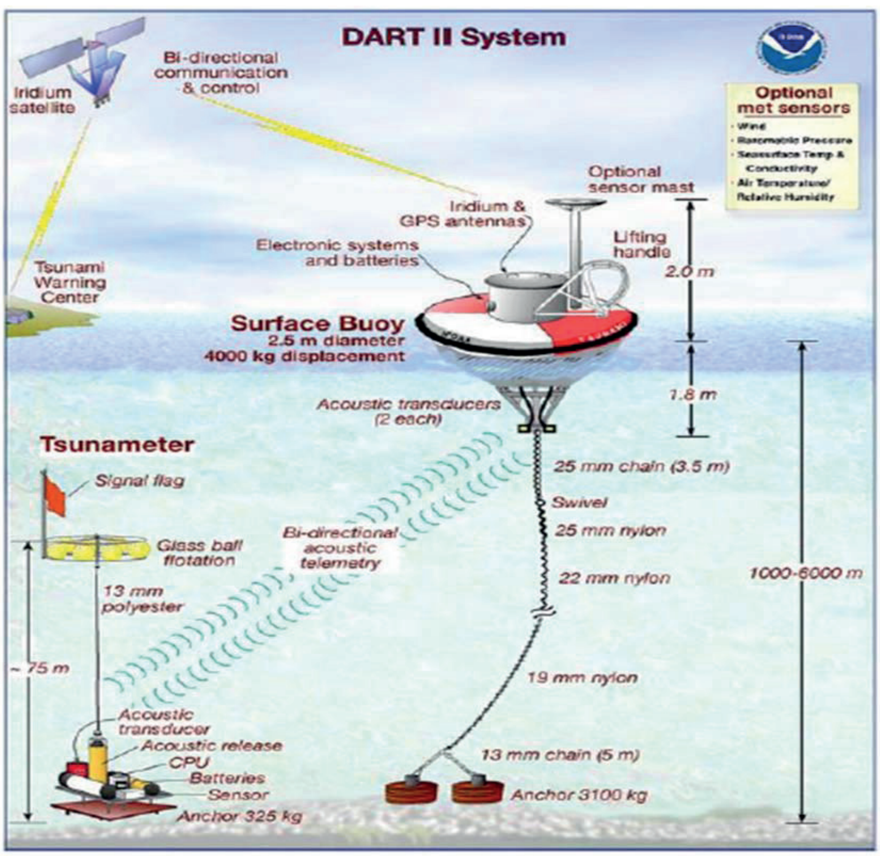

Figure 8. A schematic view of DART II (en.wikipedia.org)

generated on this panel receivable anywhere else on the same panel. Different issues caused using the SOFAR channel to communicate or transmit and receive sound signals from earthquakes in the seabed at a point adjacent to faults in the studied area. The issues are the formation of sound channel (Figure 9), the variation of physical parameters of the Arabian and Oman Sea, the way of SOFAR channel is affected as well as the disturbance of its stability because of some flows. Considering the transmission rate of earthquake signal relative to the velocity of tsunami wave, the SOFAR channel could serve as a suitable means to alert the beach dwellers before a tsunami hits Iranian coastlines.

In this method, installation of suitable equipment near the Makran or the Murray fault enables us to record any seismic activity. Furthermore, the SOFAR channel can transfer the resulting audio signal to the relevant station near the coast. Shore stations can give alerts using radio equipment. The advantage of this method includes of low maintenance and support costs. Figure 10 shows a schematic view of the way an earthquake signal is received in the vicinity of faults.

The signals are then transmitted to the shore

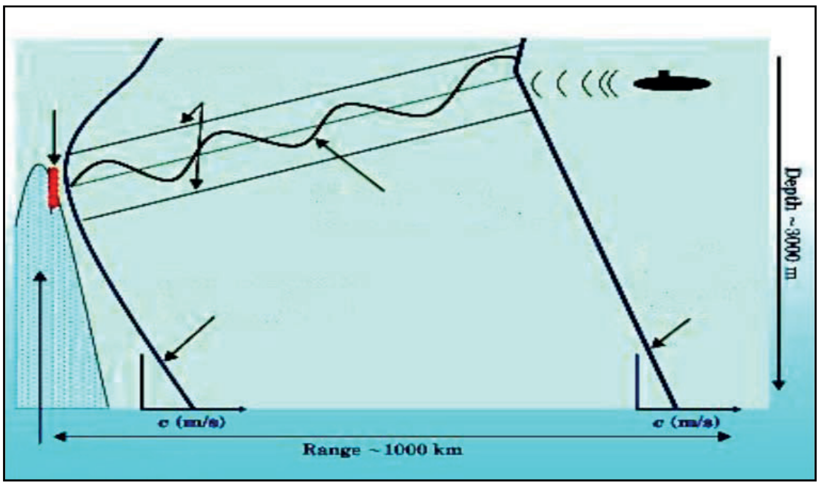

Figure 9. Formation of the SOFAR channel from the Arabian Sea to the Oman Sea, based on the physical properties of water in each region (misclab.umeoce.maine.edu)

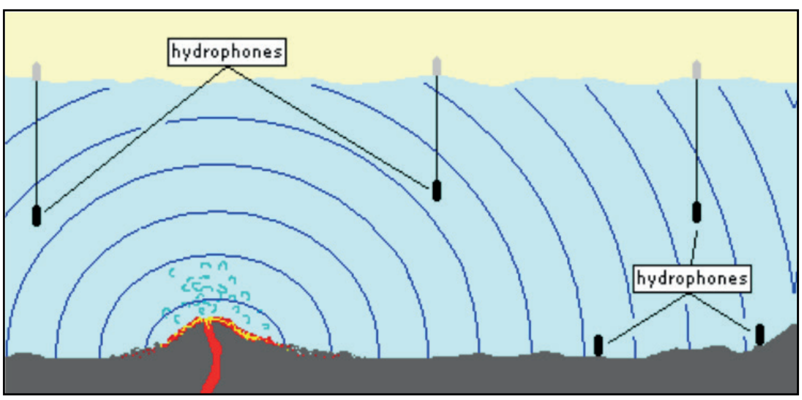

Figure 10. Procedure of seismic signal recording by installing necessary equipment near faults in the Makran Sea (dosits.org)

station via a SOFAR channel. The transmission of these signals is presented in Figure 11. In fact, seismic signals are immediately transmitted into the SOFAR channel via a cable connected to the hydrophone reception system, and the channel drives the seismic signal towards the coast. The signal reception equipment at the shore stations will transmit the received signals to the waning center (Figure 12). Currently, tide-gauge can be used to measure the seawater level variations, and assesses the probability of a tsunami wave by processing the rise or fall in sea level. A tide-gauge along with a seismograph installed on the coast, can provide a type of tsunami warning system.

In this approach, the time required for tsunami warning is short, and not every recorded seismic activity necessarily result in a tsunami event. Nevertheless, a tsunami warning systems can incorporate a seismograph, tide-gauge, buoy, and satellite communication systems (Figure 13).

In addition to the SOFAR channel, another subsidiary system can also be used as a backup tsunami warning system, but the installation, implementation and maintenance costs of this system are far more expensive and often not cost effective. This system, however, can be used for earthquake prone and tsunamigenic regions. Currently, the system is being used in some

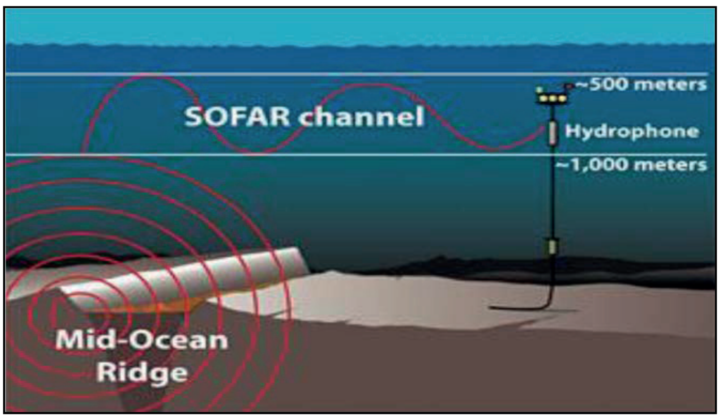

Figure 11. Transition of earthquake signals in an underwater SOFAR channel by installing the necessary equipment (whoi.edu)

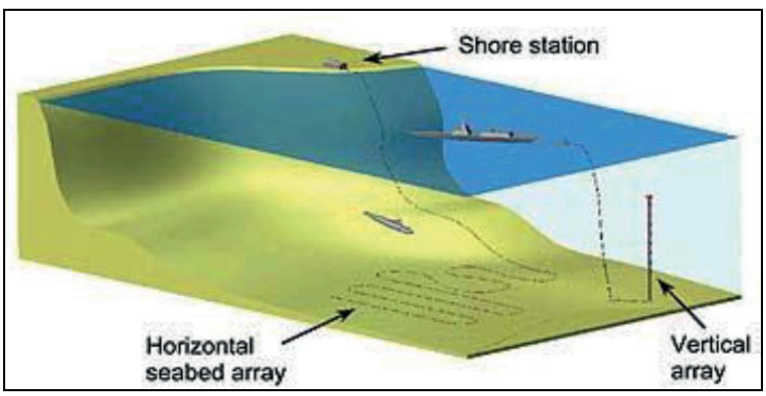

Figure 12. A shore station responsible for collecting seismic signals and transmitting them to the warning center on the shore (woodshole.er.usgs.gov)

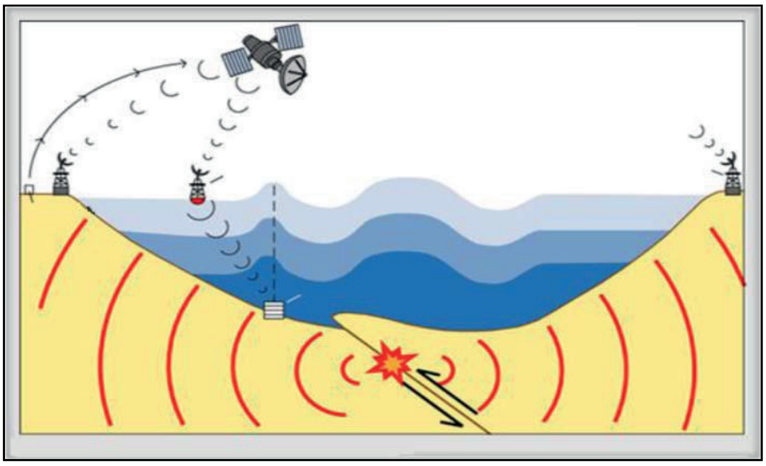

Figure 13. A conventional tsunami warning system

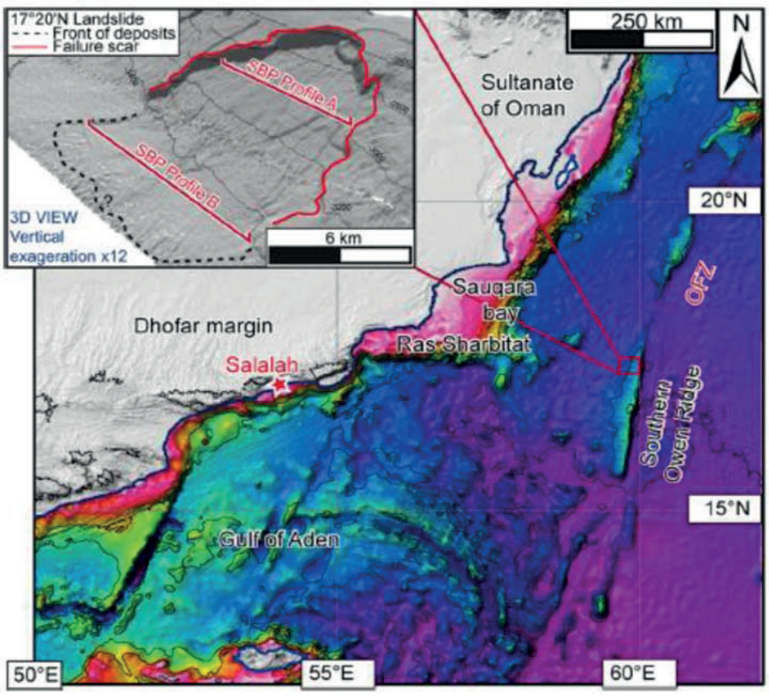

Figure 14. The topographic map of Owen Fracture Zone in the coast of Oman

parts of the world where tsunami is known as one of the most hazardous and frequent natural disasters (e.g. the shores of Japan, Indonesia, Java, etc.). The shores of the Arabian Sea have already been exposed to destructive tsunamis and cyclone-induced storms. Seismic activity in the Makran subduction zone is recognized as the main source of tsunami in the Arabian Sea, which caused the 1945 earthquake of magnitude 1.8 Richter claiming the lives of 4,000 people. The seismic activity of the Indonesian subduction zone that stands relatively away from the former zone, and has caused milder tsunami on the Arabian coast could be recognized as another source of tsunami in this zone. Although seafloor landslides have been known as the source of the deadliest tsunami in recent decades, the severity of these hazards in the Arabian Sea remains unclear. The seafloor-landslide-generated tsunami, significantly differ from the earthquake-induced tsunami. Due to smaller size of their source and their widespread frequency, the landslide-induced tsunami is much more effective, producing shorter wavelengths and narrower amplitude. Unlike the earthquake sources, the landslide sources of tsunami are characterized by greater vertical displacements resulting in generation of waves with larger amplitude. Recent discoveries about the frequent seafloor landslides along the Owen Ridge are indicative of the potential source of tsunami hazards in the Arabian Sea. The Owen Ridge is a prominent submarine relief located in 300-400 km away from the coast of Oman and is closely linked to the Owen Fracture Zone. This area is actually 800 km-long active strike-slip fault system (Figure14).

The southern segment of the Owen Ridge displays the most voluminous landslides, including two land- slides that removed up to 40-45km of sediment. Simulations show that in the event of a landslide of magnitude 7 Richter, waves with the heights ranging from 0.7 to 3.2 meters will hit the east coast of Oman. If a landslide takes place along one of the faults of the Arabian Sea or Makran Sea, it will lead to displacement and deformation of the land crust. This deformation will also affect the water surface and will propagate in form of a high wave known as tsunami wave (Figure 15). This tsunami wave is propagated to the coastlines of Iran and other countries as presented in Figure 16. Landslides along faults not far from the coastal lines of Iran could generate a tsunami capable of hitting and devastating the Iranian coastlines within a short period. Given that there is not much time to evacuate these areas and to take the necessary safety measures, it argued that all kinds of tsunami warning systems are almost inefficient.

Two types of evacuation techniques can be practices in such cases: horizontal evacuation and vertical evacuation. In horizontal evacuation, the beach dwellers must move away from coastal areas and take shelter in a safe place. However, since people don’t have enough time to get to the right distance from the coast, horizontal evacuation is almost impossible for many beach dwellers. In the vertical evacuation process, the beach inhabitants should get to appropriate height to avoid tsunami waves.

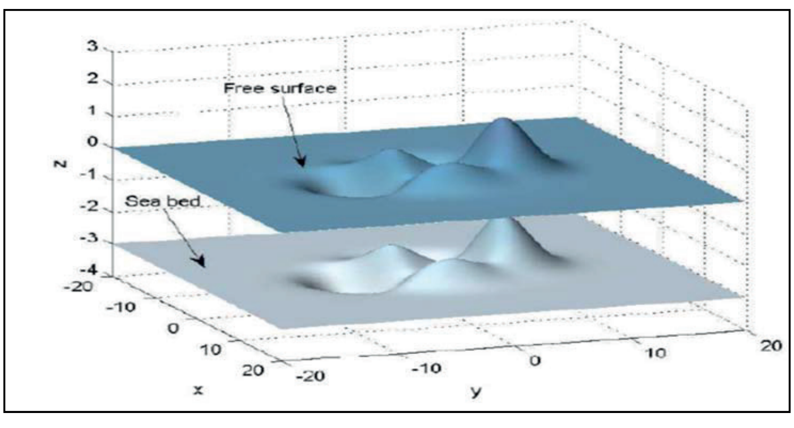

Figure 15. Deformation of seawater surface due to seafloor displacement (lama.univ-savoie.fr)

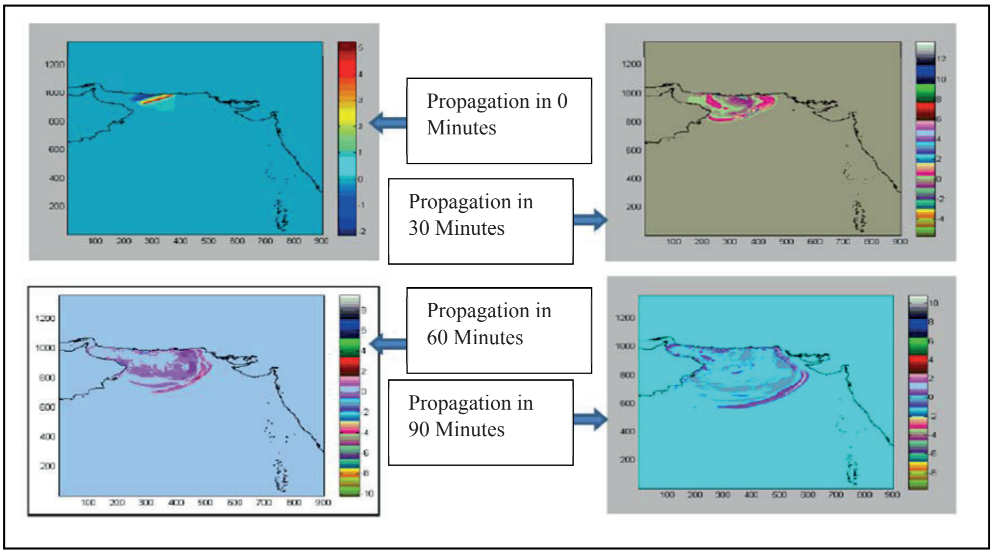

Figure 16. Scenarios of tsunami wave generation at a specific point along the Makran fault

Places with proper heights can rarely be seen in coastal areas, especially in urban and rural areas, and are difficult to be found. In such cases, it is advisable to construct suitable high structures as a safe haven in the tsunami prone coastal zones, so that beach dwellers can have immediate access to them in the event of a tsunami. Some high-rise buildings could also be used as safe heavens, provided that they are constructed according to tsunami resistance standard.

Unfortunately, the production, installation and maintenances costs incurred by DART buoys and their accessories such as the BPR, sensors and telecommunication systems is so unreasonably high that application of a large number of these systems at desired locations is not affordable. Installation of BPR on the DART system for obtaining real-time data would cost about \$100,000 - \$200,000, plus the cost of periodically replacing the equipment. The buoy and the seabed moor need to be replaced or inspected every one and two years, respectively. Although these systems are able to send real-time data much before tsunami hits the coasts, the high maintenance and replacement costs as well as difficulties associated with them make it almost cost-ineffective to keep the systems up to date, especially in areas where earthquake events are not frequent. That is why it is advisable to employ fixed systems with lower production and maintenance cost in areas such as the northwest of the Arabian Sea and in the Oman Sea along the Makran fault.

Conclusion

Utilization of SOFAR-based data transmission systems is very cost-effective, and can help collect different data used in numerical models and simulators at the same time. In case of happening a landslide at a point of the Makran fault nearest to the Iranian coast (150 km), and considering the average depth of the area which is about 2000-3000 m, the generated tsunami wave would approach the coast at 140 m/s or about 500 km/h. Furthermore, taking into account the decline in its pace in shallow areas, it will take almost 20 minutes to hit the beach. It will take the shore station almost 3 minutes to receive the generated seismic signal via the SOFAR channel. Therefore, we would have only about 17 minutes to reduce the life-threatening damage caused by the tsunami as it hits the coasts. This is the least possible time for an earthquake that occurs at the nearest point of Makran fault. Therefore, it is advisable to prepare a pattern for propagation of tsunami wave at various seismic intensities, so that one can estimate the altitude, power and travel time of the tsunami according to the location and intensity of the earthquake.

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