NUMERICAL INVESTIGATION OF FUTURE TSUNAMI HAZARD ON SRI LANKA FROM THE EARTHQUAKES OF SUMATRA-ANDAMAN REGION

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Abstract

The mega event of Indian Ocean Tsunami 26th December 2004, stressed the need for assessing tsunami hazards in vulnerable coastal areas in Sri Lanka. Two major areas of the management of disaster prevention are to evacuate people in the coastal area to safer areas as soon as possible and pre-modification of coastal structures to resist the tsunami waves effectively. Often the only way to determine the potential run-ups and inundation from a local or distant tsunami is to use numerical modeling, since data from past tsunamis is usually insufficient. It then might be possible to use such simulations to predict tsunami behavior immediately after an earthquake is detected. This paper consists of results of the numerical models of 26th December 2004 Tsunami and three other possible Tsunamis in this region which eventually can be used to create inundation and evacuation maps to minimize future damages.

Keywords: Disaster Prevention, Earthquake, Evacuation, Numerical modeling, Tsunami

6. Introduction

The 26th of December 2004 was an unforgettable day for all Sri Lankans as well as for the whole world. On that fateful day, tsunami waves struck the Eastern and Southern coasts of Sri Lanka as well as parts of Northern and Western coasts sweeping people away, causing flooding and destruction of infrastructures. When the huge waves surged up the coasts of Sri Lanka, the devastation of a tsunami brought forth a surge of generosity the likes of which the world has rarely seen. The tsunami waves were caused by an earthquake, measuring 9.1 on the Richter scale, occurred in the sea near Sumatra, Indonesia. Since many Sri Lankans did not have any previous experience of this nature, the damage caused to their lives was incredible. Thousands of people were displaced and disappeared or killed within a very short time.

The tsunami is the most formidable of all natural hazards. It is usually generated as a result of seismotectonic motions of the ocean bottom in the seismic source zone. Tsunami waves propagate far from the source and can cause damage even in regions where the earthquake was not manifested. A good definition of tsunami may be the following one: the tsunami is a series of ocean waves of extremely long wave length and long period generated in a body of water by an impulsive disturbance that displaces the water.

Large vertical movements of the Earth's crust can occur at plate boundaries. Plates interact along these boundaries called faults. Around the margins of the Pacific Ocean, for example, denser oceanic plates slip under continental plates in a process known as subduction. Subduction earthquakes are particularly effective in generating tsunamis.

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Compared with wind-driven waves, tsunamis have periods, wavelengths, and velocities tens or a hundred times larger. So they have different propagation characteristics and shoreline consequences. As a result of their long wavelengths, tsunamis behave as shallow-water waves. Shallow-water waves are different from wind-generated waves, the waves many of us have observed on a beach. Wind-generated waves usually have period of 0.5 to 20 seconds and a wavelength up to about 200 meters. A tsunami can have a period in the range of ten minutes to two hours and a wavelength in excess of 500 km (Prager, 1999).

A wave is characterized as a shallow water wave when the ratio between the water depth and its wavelength gets very small. The rate at which a wave loses its energy is inversely related to its wave length. Since a tsunami has a very large wavelength, it will lose little energy as it propagates. Hence in very deep water, a tsunami will travel at high speeds and travel great transoceanic distances with limited energy loss. For example, when the ocean is 6100 m deep, unnoticed tsunami travel about 890 km/hr, the speed of a jet airplane. And they can move from one side of the Pacific Ocean to the other side in less than one day.

7. Basic Equations of Wave Motion

7.1. The Velocity Potential

The simplest and general most useful theory is the small amplitude wave theory first presented by Airy *et al.* 1845. Solving the Laplace equation develops the small amplitude wave theory for two-dimensional periodic waves, where x and y are the horizontal and vertical co-ordinates respectively:

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=0 \tag{1}$$

With the bottom and surface conditions, the following velocity potential is obtained in an ocean of constant depth d,

$$\phi=\frac{a\sigma}{k}\frac{\cosh\ k(y+d)}{\cosh\ kd}\cos(kx-\sigma t) \tag{2}$$

for a progressive wave traveling in positive x direction. The corresponding wave profile:

$\eta = a\sin(kx-\sigma t)$ is given by,

$$\phi=\frac{a\sigma}{k}\frac{\cosh k(y+d)}{\cosh kd}\sin(kx-\sigma t) \tag{3}$$

7.2. Wavelength and Wave Celerity

The relation between wavelength, wave period and water depth is written as:

$$L=\frac{gT^2}{2\pi}\tanh(2\pi d/L) \tag{4}$$

Eqn. (4) is an implicit equation, since the unknown variable L appears both in the left and right hand sides of the equation. For given T and d values, to obtain L it may require to carry out several trial calculations. However, for convince, solutions are all ready given in graphical form, or in tables.

Wave celerity is equal to the ratio of wavelength to wave period as:

$$C=L/T \tag{5}$$

Thus using Eqns. (4) and (5) we get,

$$C = \frac{gT}{2\pi}\tanh(2\pi d / L) \tag{6}$$

$$C = \left(\frac{gL}{2\pi}\tanh(2\pi d / L)\right)^{1/2} \tag{7}$$

7.3. Constancy of Wave Period

For a simple harmonic wave train, the wave period is independent of depth. This can be proven by the following argument. Let us suppose that the wave period can depend on the depth. Let us then take a region where wave enters from one side and exit from the opposite side. Let us further suppose that at these two sides the ocean depth is different, and therefore the wave entering waves have period T_1 and the outgoing waves have period T_2. In a given time interval Δt, the number of waves which enter into the region is n_1 while, while the number of waves leaving the region is n_2 with $n_1 = \Delta t / T_1$ and $n_2 = \Delta t / T_2$.

Then, the number of waves which accumulate within the region is $n_1 - n_2 = \Delta t\ (1/T_1 - 1/T_2)$. When the time interval $\Delta t \to \infty$, the number of waves accumulated within the region will be ± depending on $T_1 >/< T_2$. This is physically unrealistic. Then the only realistic possibility is $T_1 = T_2 = T$, this result holds for any depth d.

7.4. Tsunami Wave Velocity, Wavelength and Period

Classical theory assumes a rigid seafloor overlain by an incompressible, homogeneous, and non-viscous ocean subjected to a constant gravitational field. Linear wave theory presumes that the ratio of wave amplitude to wavelength is much less than one. By and large, linearity is violated only during the final stage of wave breaking and perhaps, under extreme nucleation conditions. In classical theory, the phase velocity $c(\omega)$, and group velocity $u(\omega)$ of surface gravity waves on a flat ocean of uniform depth d are:

$$c(\omega) = \sqrt{\frac{gd}{k(\omega)d}\tanh[k(\omega)d]} \tag{8}$$

and,

$$u(\omega) = c(\omega)\left[\frac{1}{2} + \frac{[k(\omega)d]}{\sinh[k(\omega)d]}\right] \tag{9}$$

Here $k(\omega)$ is the wave number associated with a sea wave of frequency ω. Wave number connects to wavelength $\lambda(\omega)$ as $\lambda(\omega)=2\pi/k(\omega)$. Wave number also satisfies the relation:

$$\omega^2 = gk(\omega)\tanh[k(\omega)d] \tag{10}$$

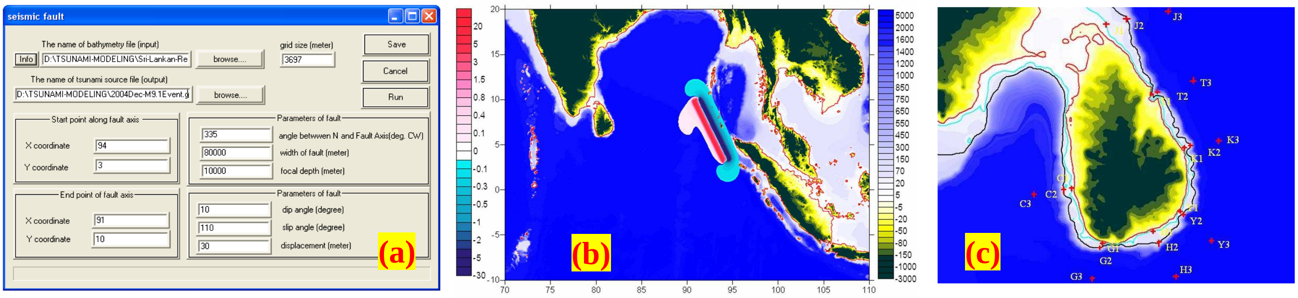
$c(\omega)$, $u(\omega)$, and $\lambda(\omega)$ vary widely, both as a function of ocean depth and wave period. Waves whose velocity or wavelength varies with frequency are called ‘dispersive’.

8. Tsunami Simulation of 26th December, 2004 Event

The tsunami generation which includes four major processes; initiation, split, amplification and run-up can be numerically modeled and compared with the available actual tsunami event data to understand the accuracy of the numerical modeling procedures and subsequently use these numerical methods to develop a tsunami evacuation maps for future disaster mitigation purposes. Here the simulations were carried out by using the AVI-NAMI (computer program developed by C++ programming language and developed/distributed under the support of UNESCO) tsunami modeling program. This chapter consists of the simulation results of the Indian ocean Tsunami 2004 (M_w= 9.1) concerning the effects around Sri Lankan island.

8.1. Analytical Model Data

The 3rd largest tsunamigenic earthquake of $M_w = 9.1$ occurred off the west coast of Northern Sumatra on 26th December 2004. There, in this mega tsunami event, the tsunami generation occurred by two major fault segments. But due to the limitation of the program (only one fault segment is permitted), the following data, as shown in Figure 1(a) have been used as the seismic fault data to initiate the seismic event and to compute the best results in the water level elevations along the coastal belt of Sri Lankan island. The Figure 1(b) shows the initial vertical sea floor offset due to the initiation of this seismic event. The Figure 1(c) shows the 21 gauge points, which were used to obtain the water level elevations arround the Sri Lankan island during this simaulation process and three gauge points have been selected for each location. The locations are denoted as: J– Jafna, T – Trincomalee, K – Kalmunai, Y – Yala, H – Hambantota, G – Galle and C – Colombo respectively.



seismic fault

The name of bathymetry file (input): D:\TSUNAMI-MODELING\Sri-Lankan-Re

grid size (meter): 3697

The name of tsunami source file (output): D:\TSUNAMI-MODELING\2004Dec-M9.1Event.g

Start point along fault axis
X coordinate: 94
Y coordinate: 3

End point of fault axis
X coordinate: 91
Y coordinate: 10

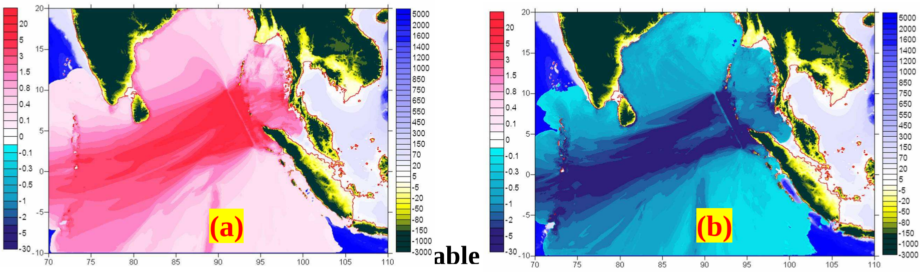
Parameters of fault
angle betwwen N and Fault Axis(deg. CW): 335
width of fault (meter): 80000
focal depth (meter): 10000

Parameters of fault
dip angle (degree): 10
slip angle (degree): 110
displacement (meter): 30

Figure 1: (a) AVI-NAMI data input file, (b) initial vertical sea floor offset for the 26th December 2004 event and (c) gauge point locations around Sri Lanka used for the simulation

8.2. Numerical Simulation Results

The Figure 2 shows the maximum and minimum water level elevations due to the simulation process of the above mentioned event of $M_w = 9.1$ Indian Ocean tsunami, 26th December 2004. Further, the Figure 3 shows the propagation of the tsunami wave and the sea states at different instants. Those results show that the first wave reach to the Sri Lankan island took about 105 min



able

Figure 2: Maximum (a) & minimum (b) water level elevations for the 26th December 2004 event

from the time of the fault rupturing near Sumatra, which is confirmed by the actual available data as well. From observations we can clearly see that the waves reach to Yala, Hambantota and Galle took about 110-120 minutes and that the western coasts was affected after about 150 minutes when we see the waves in Colombo. Also, it can be seen that there are two significant waves attacking the Sri Lankan north, eastern and south coasts and that a third wave reached the western coasts which reflected from the Maldives islands, and this was confirmed by many eye witnesses in those areas as well. So, these factors show that the predicted results are accurate enough and acceptable and hence they can be used for tsunami inundation modeling in which tsunami propagation results are continued on to shore using detailed local bathymetry and topography.

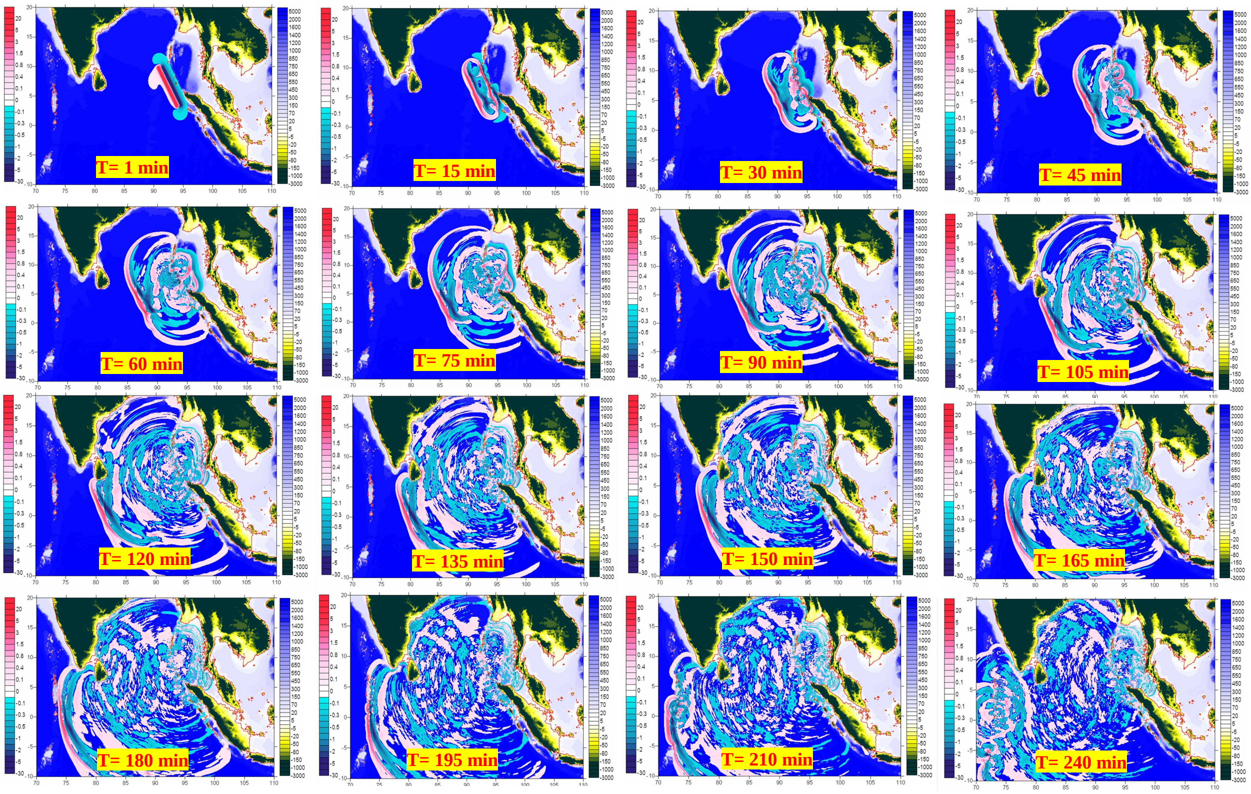


Figure 3: Sea states at different instants for 26th December, 2004 event– (M_w=9.1)

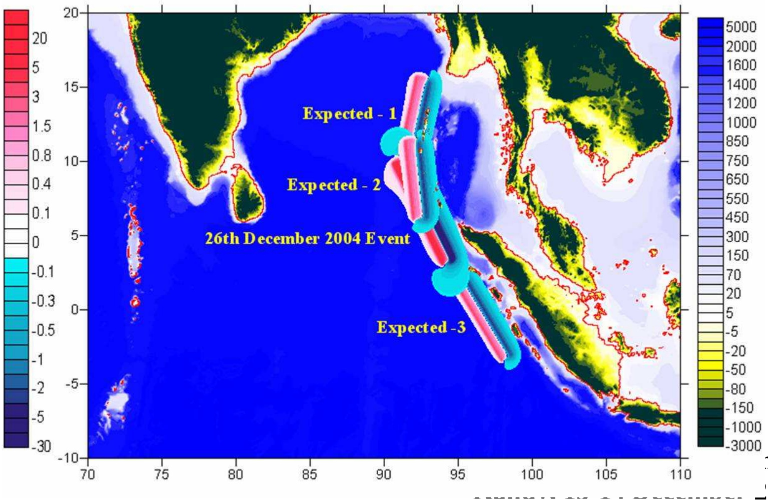
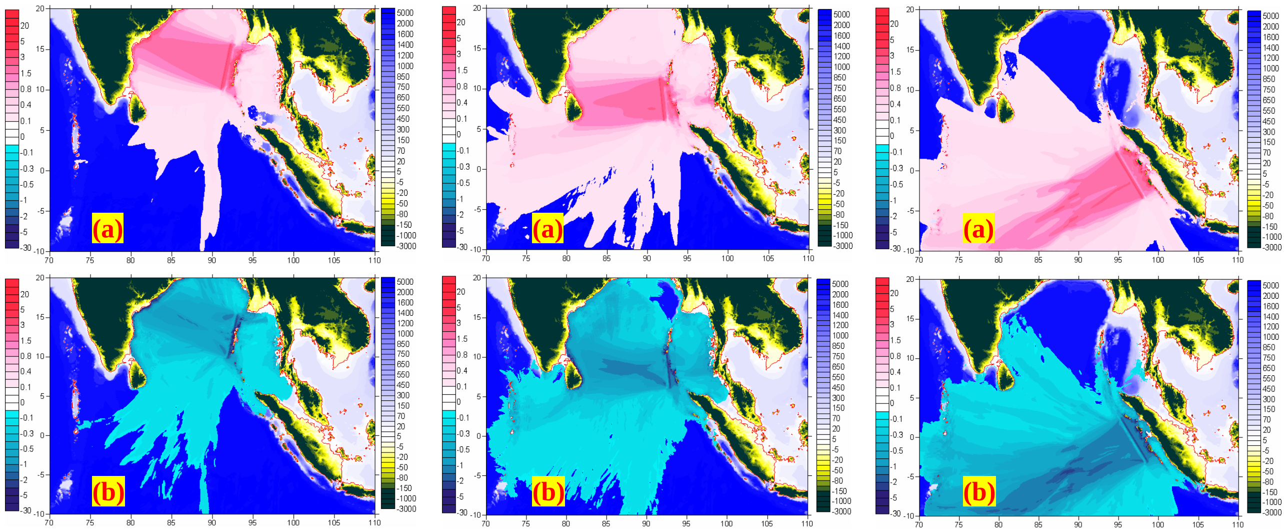


Figure 4: Four major different tsunamigenic scenarios

9. Simulation of Probable Tsunami Events

The seismic activities and historical records of great Sumatra-Andaman fault area were studied to identify the probable tsunamigenic scenarios in this region. The 1st possible scenario was identified close to the top edge of the Sumatran fault as there is a risk for the occurrence of an earthquake in that region (where energy is still to be released). And the 2nd probable tsunamigenic scenario was identified at the middle part of the Sumatran fault. But, the probability of occurrence this expected event-2 seems very low since most of the energy in this region was released due to the 2004 December and 2005 March events. According to historical records, there is a high risk of occurring of the 3rd probable tsunamigenic scenario at the most south part of the Sumatran fault, where the 1833 earthquake can repeat once again in near future. Hence, the simulation process for the above mentioned three probable tsunami events also were carried out to clarify their effects and the possible damages to Sri Lankan island and its surrounding nations. Considering the seismic records of this area, all these three probable events were modeled with an earthquake of $M_w = 8.8$ for each event. The Figure 4 shows the initial vertical sea floor offset due to those 3 probable tsunamigenic events and the 26th December,2004 event. The Figure 5 shows the maximum and minimum water level elevations 3 probable events. Further, the expected wave height and the wave arrival times of 1st leading wave and peak wave for all 3 probable events are listed in Tables 1 and 2 respectively.



Probable event-1 Probable event-2 Probable event-3

Figure 5: Maximum (a) and minimum (b) water level elevations for 3 probable tsunami events

Table 1: Expected wave height and wave arrival time of 1st leading elevation wave

City	Expected 1st wave height (m) [At 25 m deep water]			Expected 1st leading elevation wave arrival time		
	Event-1	Event-2	Event-3	Event-1	Event-2	Event-3
Jafna	0.676	2.137	-	1 hr 51 min	1 hr 56 min	-
Trincomalee	0.240	2.796	0.295	1 hr 32 min	1 hr 46 min	2 hrs 30 min
Kalmunei	0.431	2.486	-	1 hr 40 min	1 hr 47 min	-
Yala	0.494	2.381	0.323	1 hr 46 min	1 hr 42 min	2 hrs 20 min
Hambantota	0.318	1.709	0.329	2 hrs 08 min	2 hrs 06 min	2 hrs 24 min
Galle	0.161	1.013	0.319	2 hrs 10 min	2 hrs 08 min	2 hrs 26 min
Colombo	0.044	0.225	0.133	2 hrs 34 min	2 hrs 30 min	2 hrs 50 min

Table 2: Expected maximum water level elevation and the peak wave arrival time

City	Maximum expected water level elevation (m) [At 25 m deep water]			Expected peak wave arrival time		
	Event-1	Event-2	Event-3	Event-1	Event-2	Event-3
Jafna	0.676	2.137	-	1 hr 51 min	1 hr 56 min	-
Trincomalee	0.240	2.796	0.295	1 hr 32 min	1 hr 46 min	2 hrs 30 min
Kalmunei	0.516	4.001	-	2 hrs 42 min	2 hrs 20 min	-
Yala	0.505	2.381	0.529	2 hrs 58 min	1 hr 42 min	3 hrs 49 min
Hambantota	0.402	1.709	0.464	3 hrs 23 min	2 hrs 06 min	3 hrs 13 min
Galle	0.235	1.112	0.505	3 hrs 22 min	3 hrs 18 min	3 hrs 34 min
Colombo	0.063	0.225	0.133	2 hrs 57 min	2 hrs 30 min	2 hrs 50 min

Out of the three possible tsunamigenic scenario simulations, results of the first and second probable scenarios which are lying in northern Sumatra segment show that there is a huge risk of receiving devastating tsunami waves again to Sri Lankan north, eastern and south coasts if there will be an earthquake in that region. But the third probable tsunamigenic scenario (which lies on the southern Sumatra segment) simulation results show that the risk is low to receive big tsunami waves to Sri Lankan island and its surrounding nations.

We know from the historical records that some great earthquakes have occurred repeatedly in the same region: M_w=8.5 earthquake of 2005 occurred at the rupture zone of the M_w=8.7 earthquake of 1861, and the rupture zone of the 1833 M_w=8.7 earthquake encompassed the 1797 M_w=8.2 earthquake rupture zone. Though smaller tsunamigenic earthquakes of magnitude 7.5 to 8.0 have occurred more frequently, at intervals of over a few decades, like 1907 and 1935, major earthquakes occurred near the 1861 source zone. From these considerations the probability of a severe tsunami hitting Sri Lanka within a couple of decades from Andaman–northern Sumatra region appears to be low, since this area has already produced the 2004 and 2005 great earthquakes. The southern Sumatra segment is a potential zone for a great earthquake. However, Sri Lanka does not lie perpendicular to the fault in this part of the trench. Hence, damage due to tsunami from such event may not be substantial in Sri Lanka.

10. Conclusions

The numerical simulation of the Indian ocean Tsunami 2004 event of $M_w = 9.1$ and the other three expected tsunamigenic scenarios were simulated with a magnitude of $M_w = 8.8$. The findings from this study can be summarized as:

(1) The simulation results of the 26th December, 2004 mega tsunami event and the available data have very good agreeability and hence this analytical procedure can be used to obtain realistic results that can be reliably used to develop evacuation maps used to ensure public safety from tsunami.

(2) The simulation results of the other three probable tsunami events and the historical earthquake records of the great Sumatran fault area and its orientation fathomed that damage due to such tsunami event, triggered from that region may not be substantial to Sri Lankan island for couple of decades.

But, it is necessary to state that further investigation on the current seismic events on this region and other possible tsunamigenic scenarios around Sri Lankan island to be studied in detail in future to establish a more accurate decision. In any case as Sri Lankan island is located far enough from the destructive tsunamigenic plate boundaries, accurate and well timing warning can avoid that Sri Lankan people will experience another agony as we had on 26th December 2004.

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