IMPORTANCE OF NUMERICAL MODELING IN TSUNAMI DISASTER PREVENTION

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***ABSTRACT*:**

The gigantic earthquake with magnitude 9.1 occurred at the western coast of Northern Sumatra Island, on the peaceful day of 26th December 2004 and it generated the tsunami with wave height of approximately 25m in the nearby areas. The tsunami affected the whole Indian Ocean area, and the damage became one of the heaviest natural disasters in human history with casualty nearly 300,000 people as well as destructive damage to houses/buildings and infrastructures. This mega event of Indian Ocean Tsunami stressed the need for assessing tsunami hazard in vulnerable coastal areas. Two major areas of the management of disaster prevention are to evacuate the people in the coastal area to the safer areas as soon as possible and pre-modification the 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. Models can be initialized with potential worst case scenarios for the tsunami sources or for the waves just offshore to determine corresponding worst case scenarios for run-up and inundation. Models can also be initialized with smaller sources to understand the severity of the hazard for the less extreme but more frequent events. This information is then the basis for creating tsunami evacuation maps and procedures. It then might be possible to use such simulations to predict tsunami behavior immediately after an earthquake is detected and the government or the responsible authorities can take the necessary actions to evacuate the innocent residents to the safe areas shown in evacuation maps which have been created by using the numerical simulations results.

This paper consists the numerical modeling results of the December 2004 Sumatra-Andaman Tsunami which simulated with different earthquake magnitudes to demonstrate the relationship between the earthquake magnitude and the maximum water level elevations which enables to identify local and worldwide tsunamis to mitigate tsunami disasters.

KEYWORDS: Tsunami, Numerical modeling, Disaster Prevention

1. INTRODUCTION

Tsunami is a Japanese term derived from the characters "tsu" meaning harbor and "nami" meaning wave. Now generally by the international scientific community it is used to describe a series of traveling waves in water produced by the displacement of the sea floor associated with submarine earthquakes, volcanic eruptions, or landslides. 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.

Tsunamis are known with different names in different nations of the world and some of them are listed as below:

→ Tsu Nami (Harbour wave) [Japanese]
→ Maremoto [Italian, Spanish]
→ Raz-de-marèe [French]
→ Flutwellen [German]
→ Taitoko [Marquesan]
→ වරල්ල (Waralla) [Sinhalese] (Proposed)

Tsunamis can be generated when the sea floor abruptly deforms and vertically displaces the overlying water. Earthquakes are often associated with the Earth's crustal deformation; when earthquakes occur beneath the sea, the water above the deformed area is displaced from its equilibrium position. Waves are formed as the displaced water mass, which acts under the influence of gravity, attempts to regain its equilibrium. When large areas of the sea floor elevate or subside, a tsunami can be created.

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.

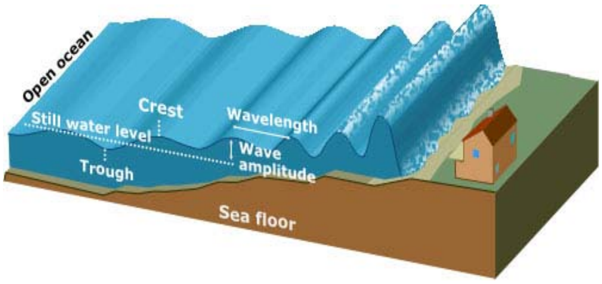

Figure 1: General view of a tsunami wave

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.

2. BASIC EQUATIONS OF WAVE MOTION

2.1 The Velocity Potential

The simplest and general most useful theory is the small amplitude wave theory first presented by Airy (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:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \tag{2.1}$$

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

$$\phi = \frac{a\sigma}{k} \frac{\cosh\ k(y+d)}{\cosh\ kd} \cos(kx - \sigma t) \tag{2.2}$$

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

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

$$\phi = \frac{a\sigma}{k} \frac{\cosh k(y+d)}{\cosh kd} \sin(kx - \sigma t) \tag{2.3}$$

2.2 Wavelength and Wave Celerity

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

$$L = \frac{gT^2}{2\pi} \tanh(2\pi d / L) \tag{2.4}$$

Eqn. (2.4) 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:

$$C = L/T \tag{2.5}$$

Thus using Eqns. (2.4) and (2.5) we get,

$$C = \frac{gT}{2\pi} \tanh(2\pi d / L) \tag{2.6}$$

$$C = \left(\frac{gL}{2\pi} \tanh(2\pi d / L) \right)^{1/2} \tag{2.7}$$

2.3 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 $\Delta t \rightarrow \infty$(infinity), the number of waves accumulated within the region will be $\pm \infty$ (infinity) 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.

2.4 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(ω), and group velocity u(ω) of surface gravity waves on a flat ocean of uniform depth d are:

$$c(\omega) = \sqrt{\frac{gd}{k(\omega)d} \tanh[k(\omega)d]} \tag{2.8}$$

and

$$u(\omega) = c(\omega)\left[\frac{1}{2} + \frac{[k(\omega)d]}{\sinh[k(\omega)d]}\right] \qquad (2.9)$$

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

$$\omega^2 = gk(\omega)\tanh[k(\omega)d] \qquad (2.10)$$

c(ω), u(ω), and λ(ω) vary widely, both as a function of ocean depth and wave period. Waves whose velocity or wavelength varies with frequency are called ***dispersive.***

3. THE GREAT EARTHQUAKE & MEGA TSUNAMI ON 26TH DECEMBER 2004

The most fatal, destructive, tragic and significant disaster caused by the Tsunamis in recent memory was the one occurred in peaceful morning on the 26th day of December 2004. This was with a magnitude of a 9.1 earthquake in the Northwest coast of the Indonesian island of Sumatra. The earthquake resulted from complex slip on the fault where the oceanic portion of the Indian Plate slides under Sumatra, part of the Eurasian Plate. The earthquake deformed the ocean floor, pushing the overlying water up into a tsunami wave.

The Asian Tsunami of December 2004 left an unprecedented trail of destruction in my motherland Sri Lanka and around much of the Indian Ocean. When they arrived with little or no warning, the mega-waves were ruthless and indiscriminate. The tsunami wave devastated nearby areas where the wave may have been as high as 25 meters and killed nearly 300,000 people from nations in the region and tourists from around the world. In overall terms, its level of destruction is higher than in Lisbon earthquake (1755 AD) which is regarded as the deadliest earthquake in modern history which took well over 100,000 lives in Lisbon city.

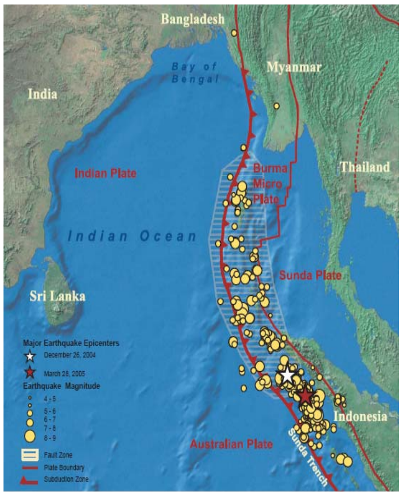

Figure 2: The earthquake epicenter, aftershocks, and the extent of the main fault rupture for the M=9.1 December 26, 2004 earthquake and the M=8.7 March 28, 2005 earthquake. [Map taken from: Indian Ocean tsunami report of Risk Management Solutions, USA]

On December 26, 2004 at 06:58:53 local time (00:58:53 GMT), a fault rupture was initiated off the west coast of northern Sumatra, Indonesia along the Sunda Trench subduction zone plate boundary, triggering a devastating tsunami around much of the Indian Ocean. The epicenter (the point on the Earth's surface above which the rupture initiated) was located at 3.30ºN and 95.87ºE, approximately 250 km south-southeast of Banda Aceh, the capital city of the Aceh Province in northern Sumatra, Indonesia. From this point, the rupture continued to expand northward for more than 1,200 km, generating a massive M=9.1 earthquake.

The earthquake rupture was located at a relatively shallow depth along the subduction zone; estimates of the focal depth range from 10 to 30 km. The aftershock distribution suggests a main fault rupture zone of 90 km in width, extending along the 1,200 km rupture up to the Andaman Island chain. Total fault movement was around 15 m near Sumatra, with decreasing displacement to the north. In this region, the Indian Ocean plate is moving down to the east under the Burma Microplate at a rate of 5.9 cm per year, so the displacement represented up to 250 years of accumulated plate motion. Hundreds of aftershocks were recorded in the following days and months, including a second significant, M=8.7 earthquake on March 28, 2005 at 23:09:36 local time (16:09:36 GMT).This earthquake was located at 2.076°N, 97.013°E, southeast of the epicenter of the December 2004 earthquake. This second major shock caused further building damage and triggered another, albeit much smaller and localized, tsunami.

4. TSUNAMI SIMULATION

The paper is basically contained the results of six different simulations 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. In this part of the research, the Indian ocean Tsunami 2004 (M_w= 9.1) and the same scenario with five other different earthquake magnitudes (M_w= 8.8, 8.5, 8.0, 7.5 and 7.0) were simulated and the water level elevations along the coastal belt of Sri Lanka were calculated to investigate the relationship between the earthquake magnitude and the maximum water level elevations.

4.1 26th December, 2004 Event – (Mw = 9.1)

In the 26th December 2004 Sumatra event, the tsunami generation occurred by two major fault segments. But due to the limitation of the program we have used (only one fault segment is permitted), the following data（Figure 3）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.

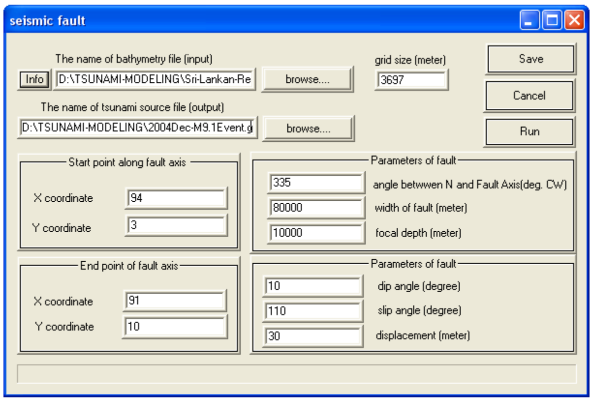

Figure 3: AVI-NAMI Data input file for the 26th December 2004 Event

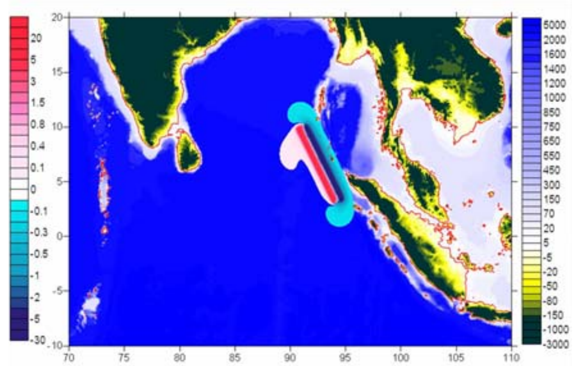

Figure 4: Initial Vertical Sea Floor Offset for the 26th December 2004 Event

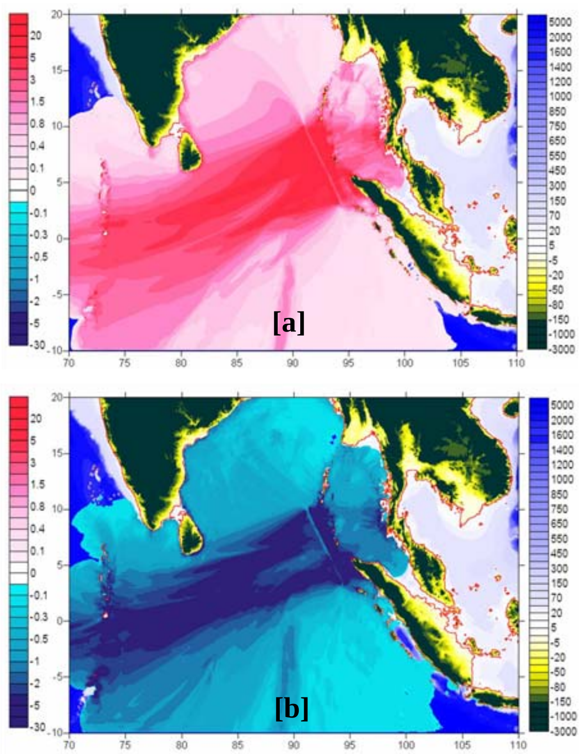

Figure 5: Maximum[a] and Minimum[b] Water Level Elevations for the 26th December 2004 Event

The above figure 4 shows the initial water level elevation and the figure 5 shows the maximum and the minimum water level elevations due to the simulation process of the above mentioned 26th December 2004 event with $M_w = 9.1$.

Also the following figure 6 shows the gauge points used to obtain the water level elevations around the Sri Lankan island during this simulation process and they are noted as follows:

J – Jafna	T – Trincomalee
K – Kalmunai	Y – Yala
H – Hambantota	G – Galle
C – Colombo	

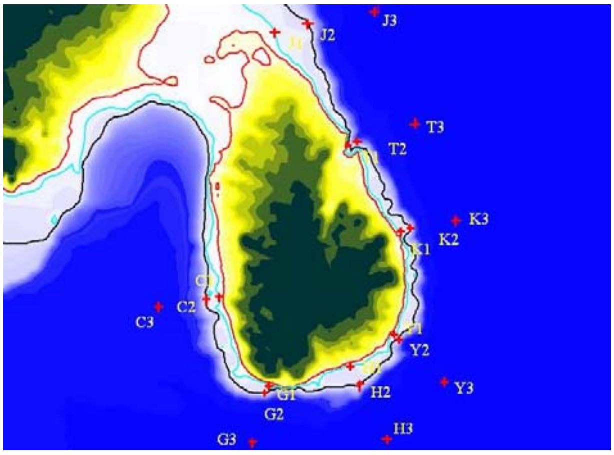

Figure 6: Gauge point locations around Sri Lanka used for the Simulation

4.2 Simulation of 26th December, 2004 Event with Different Earthquake Magnitudes

According to the empirical relationships among Magnitude(M), Rupture Length(L), Rupture Width(W) and Surface Displacement(S) introduced by D.L. Wells and K. J. Coppersmith in 1994 which are shown below,

$$\mathrm{Log}(L) = 0.59*M - 2.44$$
$$\mathrm{Log}(W) = 0.32*M - 1.01$$
$$\mathrm{Log}(S) = 0.69*M - 4.80$$

fault ruptures were created for different earthquake magnitudes and simulated to find out the differences of water level elevations with respect to the magnitude of the event. More details of the data used to produce those events with different magnitudes are displayed in Table 1.

In this part of the research, Tsunami simulation process was carried out with different earthquake magnitudes, such as M_w = 8.8, 8.5, 8.0, 7.5 and 7.0. The same gage points were used during the all simulations and the water level variations were observed. The following figure 7 shows the maximum and minimum water level elevations during those 5 simulations respectively.

Table 1: Corresponding Fault Data for Different Earthquake Magnitudes

Fault Data	**Magnitude**					
	9.1	**8.8**	**8.5**	**8.0**	**7.5**	**7.0**
Start X Coordinate (°E)	94	93.5	93	93	92.75	92.75
Start Y Coordinate (°N)	3	4	4.75	5.5	5.75	6
End X Coordinate (°E)	91	91.5	92	92	92.25	92.25
End Y Coordinate (°N)	10	9	8.25	7.5	7.25	7
Fault Length (km)	850	590	375	200	100	50
Width of the Fault (km)	80	65	50	35	25	17
Focal Depth (km)	10	10	10	10	10	10
Displacement (m)	30	20	12	6	3	1

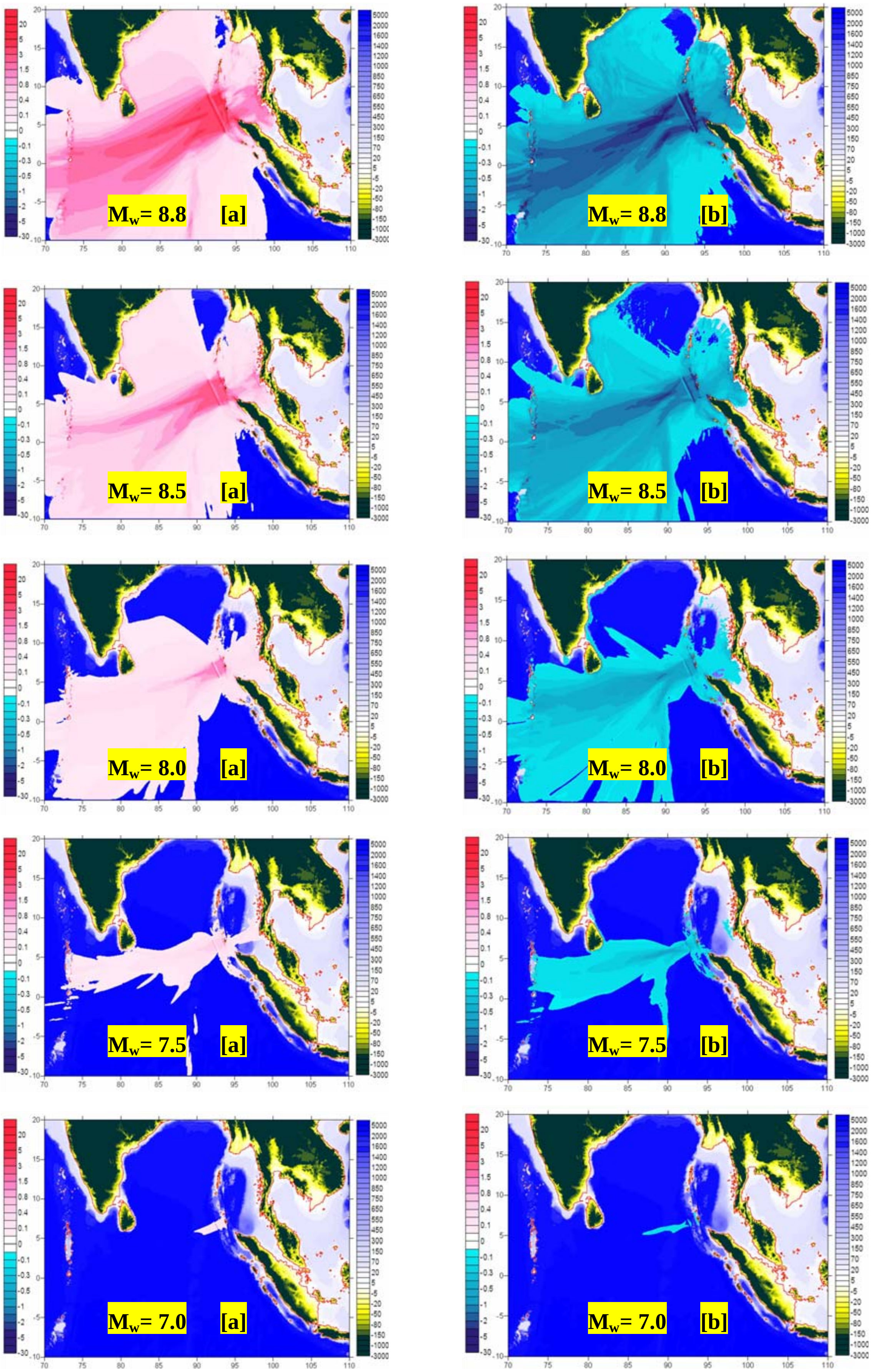

Figure 7: Maximum[a] and Minimum[b] Water Level Elevations of Different Magnitude Events

5. RESULTS

The following figure 8 shows sea states during the numerical simulation process of the 26th December 2004 Sumatra Tsunami event. It can be clearly observed that the tsunami wave reaches the southern coastal area of the island at about 115 min after the fault rupturing near Sumatra.

The figure 9 shows the water level fluctuation of sea at 25m depth close to the Yala city of Sri Lanka with respect to deferent earthquake magnitude tsunami events. And the figure 10 shows the maximum water level variation in the seven cities used for this analysis in different earthquake magnitude tsunami events.

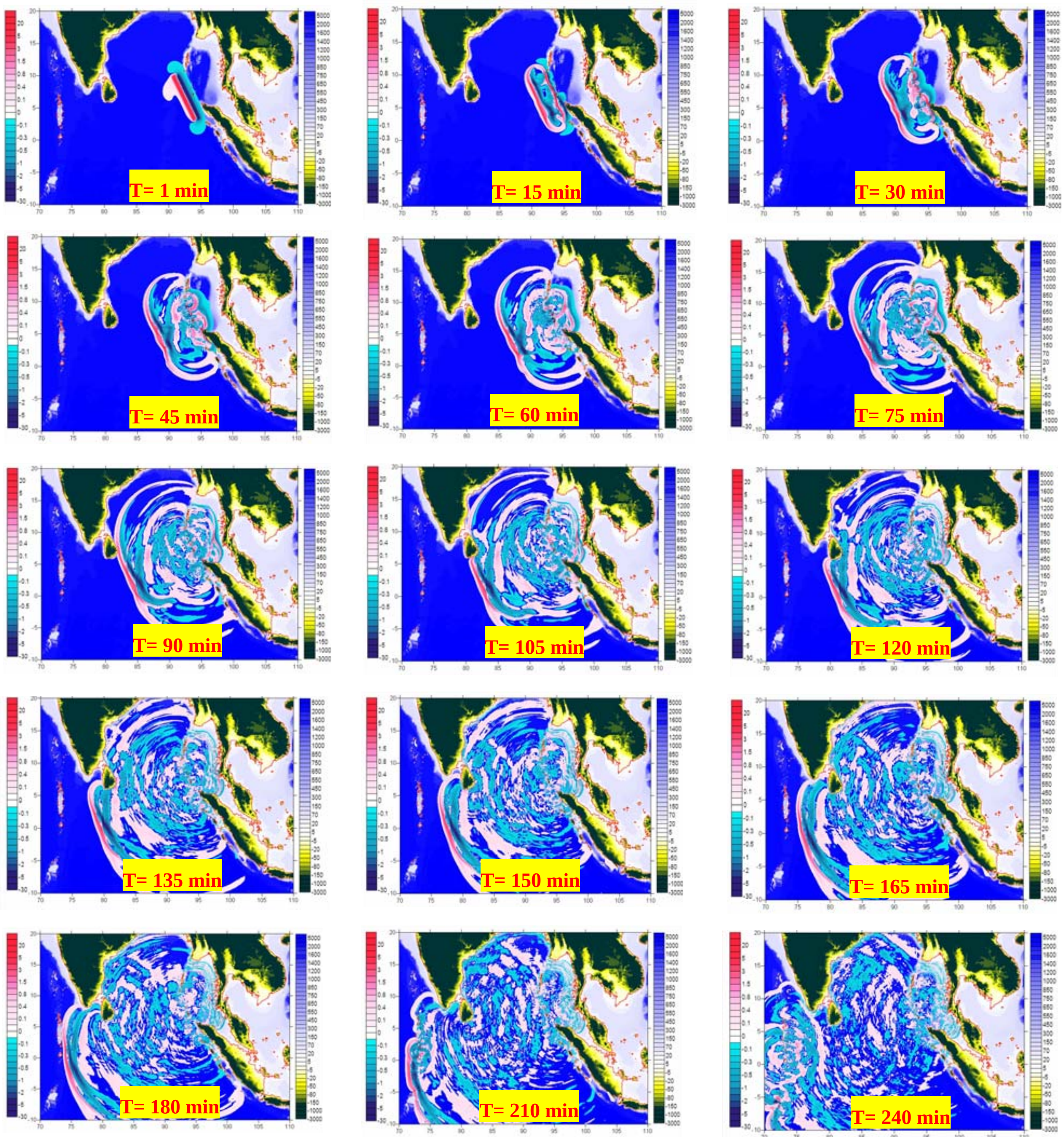

Figure 8: Sea States at Different Instants for 26th December, 2004 Event– (M_w=9.1)

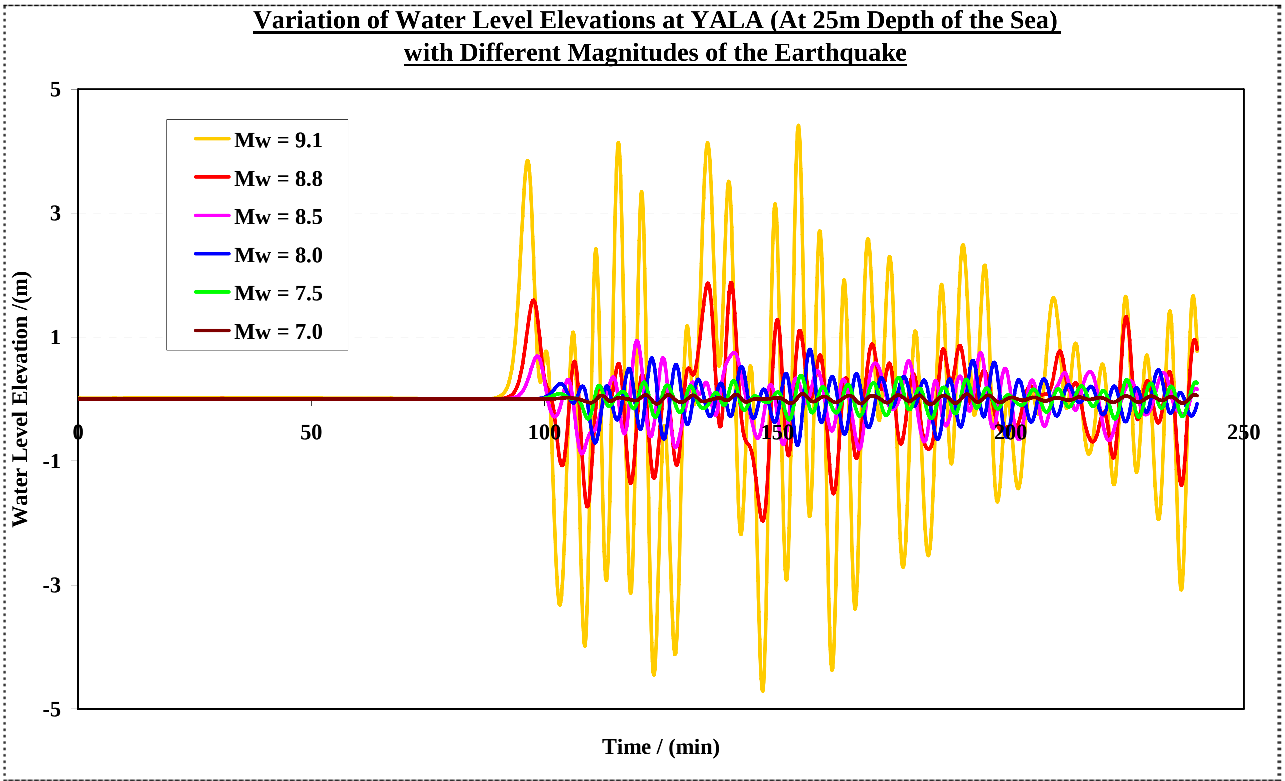

Figure 9: Water Level Elevation at YALA vs. Earthquake Magnitude at 25 m Sea depth

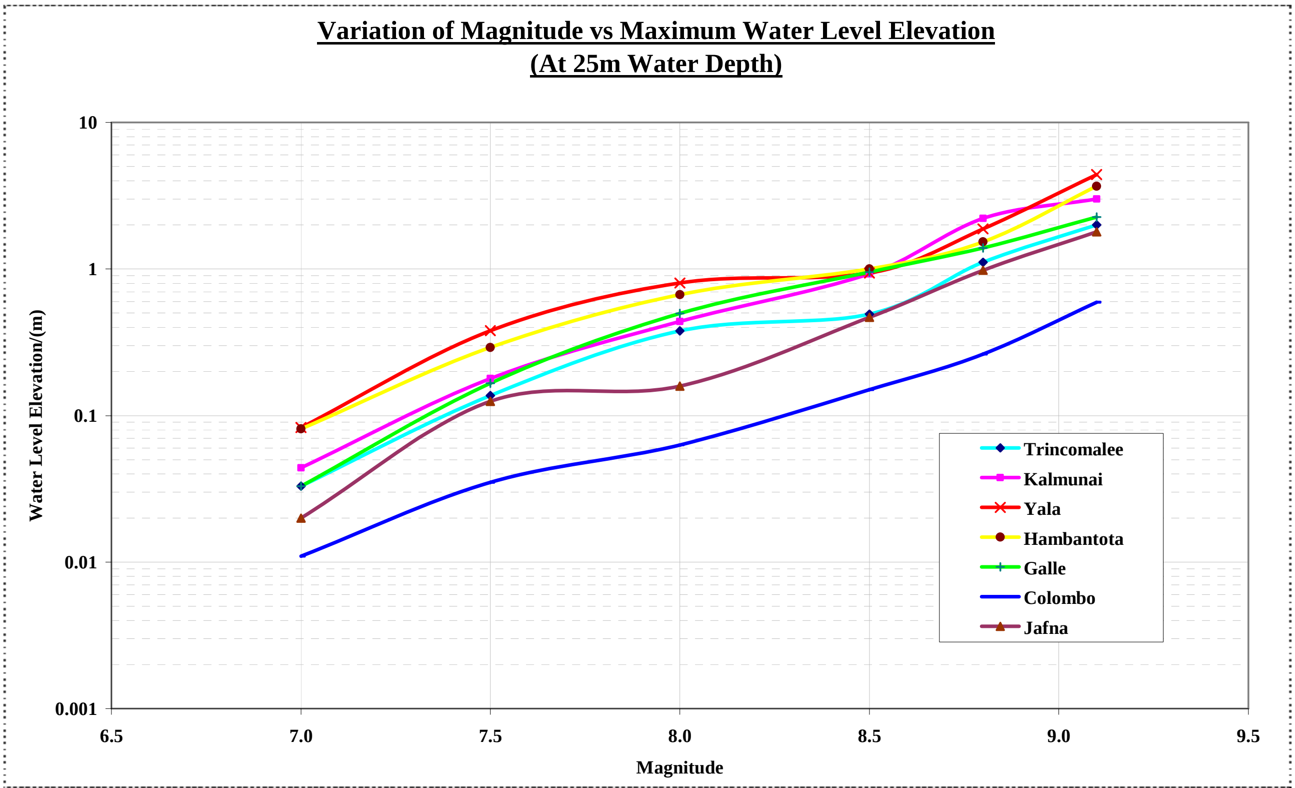

Figure 10: Maximum Water Level Elevation vs. Earthquake Magnitude at 25 m sea depth

6. CONCLUSIONS

The numerical simulation results show that the first wave reach to the Sri Lankan island took about 115 min 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 we can see 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 can be used for tsunami inundation modeling in which tsunami propagation results are continued on to shore using detailed local bathymetry and topography. Then it is possible to obtain realistic results that can be reliably used to develop evacuation maps used to ensure public safety from tsunami.

By considering the water level variation with respect to the magnitude of the earthquake (Figure 10), it is very clear that the water levels are not much significant till the earthquake magnitude M_w= 8.5, which it can be categorized as ***'Local Tsunami'*** event. On the other hand it is noted that, beyond M_w= 8.5, water levels increase enormously creating a ***'World wide Tsunami'*** *event.*

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 may not be substantial in Sri Lanka. 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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