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APPLICATION OF MATLAB IN UNDERSEA EARTHQUAKE SIGNAL PROCESSING FOR TSUNAMI FORECASTING

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Abstract- The Great Tohuku, Japan earthquake (Mw=9.0) of 11th March 2011 caused severe hazard in Japan and neighbouring countries and revealed the importance and need of warning systems to minimize the casualties. Several methods are available for predicting tsunamis, but these methods are time consuming and not easy to apply in practical and real situations. They mainly rely on the tsunami water level information and modelling of various stages of the tsunami propagation and simulation of the tsunami wave heights and are mainly associated to the near field stations.The whole process takes time and consequently issuing warning delays and turns out to be unusable. So in this paper we have attempted signal analysis tool such as the Continuous Wavelet Transform (CWT) and supported by the Fast Fourier Transform (FFT) technique for quick estimations of Tsunami warnings for overcoming the above drawbacks. In this technique first few minutes' seismograms of the earthquakes events are used for the purpose. The frequency content of these seismic signals has been studied to quantify the energy content in high frequency. It is observed that wavelet coefficients for frequencies greater than 0.33 Hz (scale below 50) tsunamigenic earthquakes do not show significant energy in the spectrum. However, significant energy is found in spectrum of non-tsunamigenic earthquake. This is confirmed by FFT analysis. In this paper we present the wavelet analysis on the Great Tohuku, Japan earthquake of 11th March, 2011. Some other global tsunamigenic and non-tsunamigenic undersea earthquake events are also analyzed for test and comparison of the used methodology.

Keywords- Sea Earthquake, Tsunami Predictions, Wavelet analysis.

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Introduction

The word 'Tsunami' is of Japanese origin, which means, "harbor wave". Tsunamis are large waves that are generated when the see floor is deformed by seismic activity, vertically displacing the overlying water in the ocean. The quake occurred at a place where several massive geological plates push against each other with massive force. Tsunami has very low height while traveling over Deep Ocean. High waves occur only when it reaches the shallow waters, typically near the coast. Tsunamis can occur in all oceans, but they are most common in the Pacific. In this century, more than 200 tsunamis have been recorded in the Pacific. Areas thousands of miles from an earthquake can be struck by a resulting tsunami. The waves appear to be normal ocean waves until they approach the coastline, where a gigantic wall of water can build on the ocean surface. Tsunamis reaching heights of more than 100 feet have been recorded.

On 11th March 2011, a devastating Great Tohuku, Japan earthquake (Mw=9.0) triggered Off the Pacific Coast of Tohuku. Its hypocentre located ~70 Km East of Oshika Peninsula of Tohuku at ~ 32 km depth underwater. It triggered powerful tsunami waves, which reached up to the heights of 40.5 meters and travelled up to 10 km inland. Tsunami caused loss of several thousand lives, destruction of infrastructure and number of nuclear accidents. To minimize such havoc losses due to tsunami, an effective early tsunami warning system is required. High quality recording of Broad Band seismograms at the Wadia Institute of Himalayan Geology (WIHG) stations in India motivated us to understand the physical characteristics of tsunamigenesis. Tsunami is a complex phenomenon to understand. Its complexity mainly lies in its generation and propagation as it is not related to the seabed conditions only but also related to fault parameters.

Several methods are available for predicting tsunamis. But these methods are time consuming and not easy to apply in practical and real situations. One approach is; receiving the information from the DART buoys deployed in the deep oceans. The tsunami has to reach these buoys and then tsunami water level information is transferred to early warning centers. But this whole process takes time consequently issuing warning delays and turns out to be unusable.

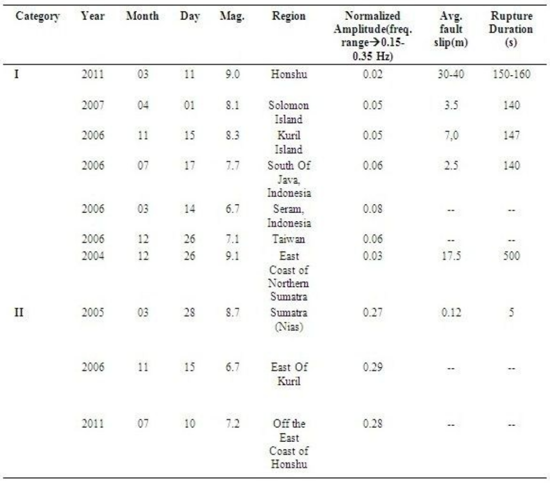
Another approach is modeling of all the stages of tsunami propagation and simulation of wave heights and run up heights at the far-field locations before the arrival of the tsunami. This method needs precise magnitude estimation and fault parameters. The time of arrival of tsunami at coastal areas nearby the epicenter region is less as compared to the time taken for the simulation process. Therefore, this method is appropriate to understand tsunami behavior and to estimate far-field effects, but not suitable to issue early warning.

The applications of the wavelet analysis are vast in different fields of signal processing. In seismology, wavelet transform has also been used by different workers for seismogram analysis, earthquake parameter determination and for tsunami warning [12], [9], [4]. Wavelet transform is a localized transform in both time and frequency, which is more appropriate than conventional methods to extract information from a non-stationary signal. Wavelet transform was first introduced by [10], [11] [8] and [7] and used it as a powerful signal analysis tool in different fields of applications such as de-noising, compression and time-frequency analysis [6], [2], [3], [13].Unfortunately, many studies using wavelet analysis have suffered from an apparent lack of quantitative results. The wavelet transform has been regarded by many as an interesting diversion that produces colourful pictures, yet purely qualitative results. This misconception is in some sense the fault of wavelet analysis itself, as it involves a transform from a one dimensional time series (or frequency spectrum) to a diffuse two dimensional time frequency image. This diffuseness has been worsened by the lack of statistical significance tests [13].

Tsunamis travel with the speed of 500 to 700 Km/hr and earthquakes can be detected almost at once as seismic waves travel with a typical speed of about 4Km/s. Therefore, if these seismic signals can be used as an indication of tsunamigenesis of earthquake, there will be some buffer time for tsunami warning to be issued to the threatened areas.

Here we have attempted signal analysis tool such as the Continuous Wavelet Transform (CWT) and supported by the Fast Fourier Transform (FFT) technique for distinguishing the tsunamigenic and non-tsunamigenic earthquakes based on the frequency content in time- scale domain from near-field as well as far-field stations for overcoming the above drawbacks. Considering only first few minutes of the P-wave train, the frequency content of the seismogram is analyzed for different tsunamigenic and non-tsunamigenic earthquakes. The seismograms of earthquake events from Great TohukuJapan 11th March 2011, East of Kuril Island 15th November, 2006, and others as specified in Table 1 are taken for illustration of the methodology.

Table1- shows the Earthquake events used in calculating "Max Ea" parameters. Category I are Tsunamigenic and II are Non-Tsunamigenic events



Category	Year	Month	Day	Mag.	Region	Normalized Amplitude(freq. range→0.15-0.35 Hz)	Avg. fault slip(m)	Rupture Duration (s)
I	2011	03	11	9.0	Honshu	0.02	30-40	150-160
	2007	04	01	8.1	Solomon Island	0.05	3.5	140
	2006	11	15	8.3	Kuril Island	0.05	7,0	147
	2006	07	17	7.7	South Of Java, Indonesia	0.06	2.5	140
	2006	03	14	6.7	Seram, Indonesia	0.08	--	--
	2006	12	26	7.1	Taiwan	0.06	--	--
	2004	12	26	9.1	East Coast of Northern Sumatra	0.03	17.5	500
II	2005	03	28	8.7	Sumatra (Nias)	0.27	0.12	5
	2006	11	15	6.7	East Of Kuril	0.29	--	--
	2011	07	10	7.2	Off the East Coast of Honshu	0.28	--	--

Data Used

To understand the tsunamigenesis, we have analysed under sea earthquakes triggered in Off the Pacific Coast of Tohuku, Japan in Pacific Ocean region and XX number of other global undersea earthquakes for better comparison of results. The seismograms recorded by the seismic stations of Wadia Institute of Himalayan Geology (WIHG) in NW Himalaya, India are used in the present study for well estimation of results using wavelet and FFT analysis. All the earthquakes data are recorded at 100Hz sampling frequency at different stations of WIHG. The first few minutes (less than 5 min in most cases) comprising the P-wave train of the seismograms are used to quantify the energy content in high frequencies (i.e. more than 0.33 Hz). However the analysis is done on first 15 minutes of Seismogram for FFT analysis.

Method of analysis

A wavelet based methodology supported by FFT analysis has been used to predict tsunamigenesis by differentiating tsunamigenic earthquakes from non–tsunamigenic earthquakes based on frequency content of the seismic signals and quantify the energy content in high frequencies. In the continuous wavelet analysis, the scaled and translated wavelets are used, which make it suitable for studying the non-stationary signals. Significant information can be extracted simultaneously in time as well as frequency domain due to time-frequency localization property of the wavelets. Due to this time-frequency localization property, the wavelet transform gives better decomposition of signal in spectral domain than the conventional Fourier transform or windowed Fourier transform. Continuous wavelet transform uses wavelength adaptive convolution operators that are optimal on the basis of wavelength of the studied portion of a signal. It allows the analysis of both local as well as global features and thus, acts as a microscope in spectral analysis. The seismograms are non-stationary waveforms and can be dealt accordingly in wavelet analysis.

The Continuous Wavelet Transform (CWT) of a function f(t) is mathematically given as following:

$$w_{\psi/f}(a,b)=\int_{-\infty}^{+\infty}\frac{1}{\sqrt{a}}\psi^{*}(\frac{t-b}{a})f(t)dt, a,b\in R, a>0$$

ψ^{*} is a complex conjugate of analyzing wavelet

$\psi(t)$ which is also known as mother wavelet or Kernel wavelet, ‘a’ is the scale factor which is inversely proportional to frequency and ‘b’ is the translation parameter. The value of 1/√a is used to normalize at various scales [5].

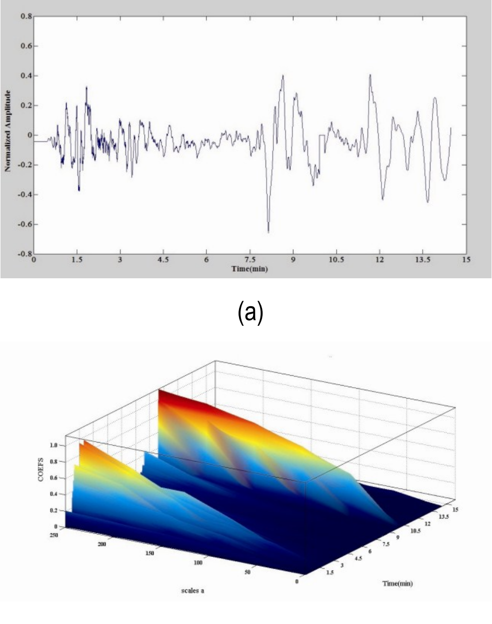
The wavelet coefficients are calculated for first few minutes of the seismogram and sum of the wavelet coefficient (W) for high frequency (scale below 50) are used for identifying the tsunamigenesis. In this high frequency band the total energy of the signal can be presented as following:

$$Ea = \sum_{a} |W|^{2} \qquad (2)$$

The total energy (Ea) at different times for high frequencies is calculated for characterizing the tsunamigenesis. The parameter used to distinguish tsunamigenic and non-tsunamigenic earthquake is “max Ea” which is the maximum value of “Ea” among all times.

Results and Discussion

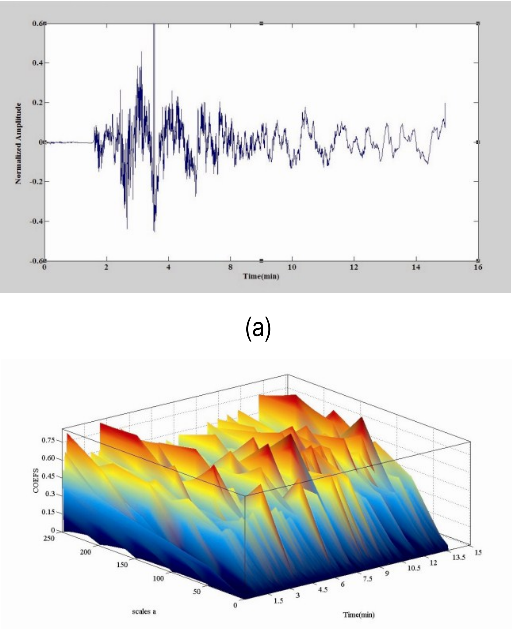
The wavelet spectrum of various seismograms shows a distinct behaviour of the wavelet coefficients for frequencies greater than 0.33 Hz (scale below 50). Tsunamigenic earthquakes are not showing any significant energy for higher frequencies. However, the energy for these frequencies is significant for non-tsunamigenic earthquakes. The wavelet spectrum of the, Great Tohuku Japan earthquake 11th March, 2011 and East of Kuril Island 15th November, 2006 are shown in Fig.1 and Fig.2 respectively.



(a)

(b)

Fig.1- (a) Seismogram ,(b) wavelet spectrum of 11thMarch, 2011 Great Tohuku Japan earthquake (tsunamigenic).

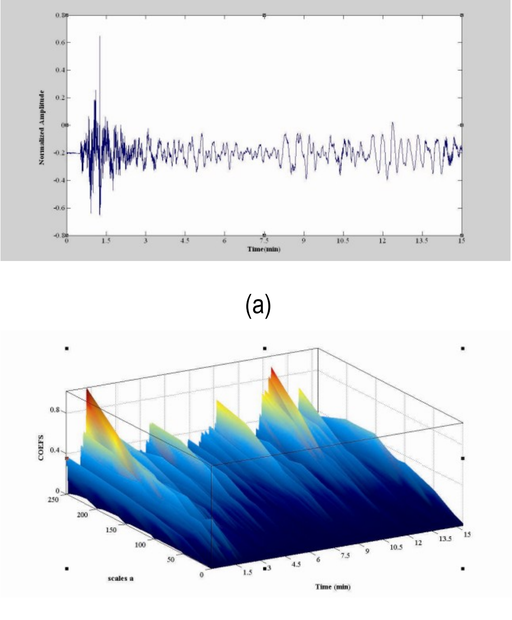


(a)

(b)

Fig.2- (a)Seismogram ,(b)wavelet spectrum of 15thNovember,2006East Kuril Island, Russia (non-tsunamigenic).

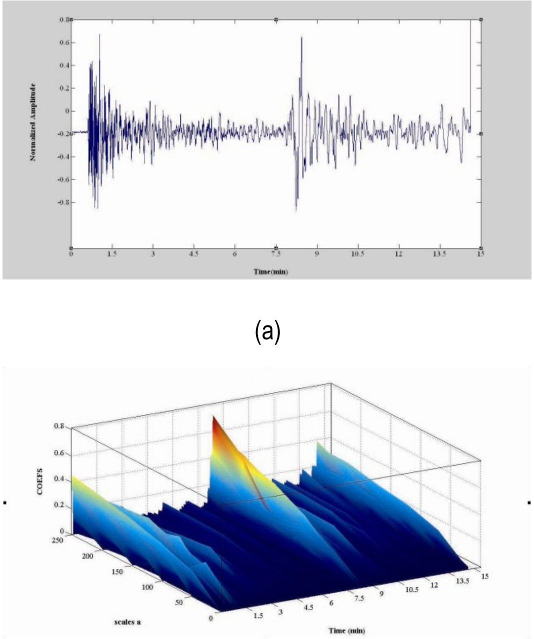
The figures clearly indicate the absence of high frequencies for tsunamigenic earthquake (Great Tohuku, Japan 11th March, 2011) and presence of high frequencies for non-tsunamigenic earthquake (East of Kuril Island 15th November, 2006). Similar characteristics are observed for other seismograms considered in the study. Seismograms and CWT spectrum of the Kuril Island, Seram Island, South of Java and Sumatra 2004 earthquakes are shown in Figs. 3 to 6 respectively.



(a)

(b)

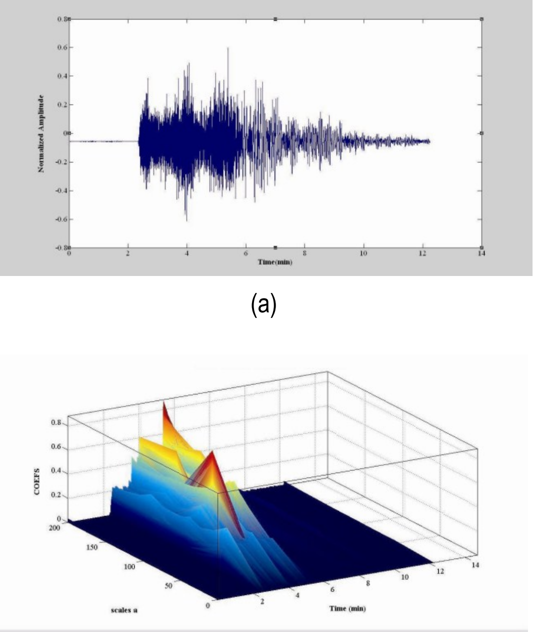
Fig.3- (a)Seismogram,(b) wavelet spectrum of 15thNovember, 2006 Kuril Island, Russia (tsunamigenic).



(a)

(b)

Fig.4- (a) Seismogram,(b)wavelet spectrum of 14th March, 2006 Seram Island, Indonesia (tsunamigenic).



(a)

(b)

Fig.5- (a)Seismogram,(b)wavelet spectrum of 24thDecember, 2004 Sumatra Island, Indonesia (tsunamigenic).

The total energy "Ea" for the scale ranging from 50 to 250 is calculated for different seismograms. The variation of "max Ea" with time for Great Tohuku Japan earthquake (tsunamigenic) and East of Kuril island (non-tsunamigenic) earthquake is shown in Figs. 7 and 8 respectively.

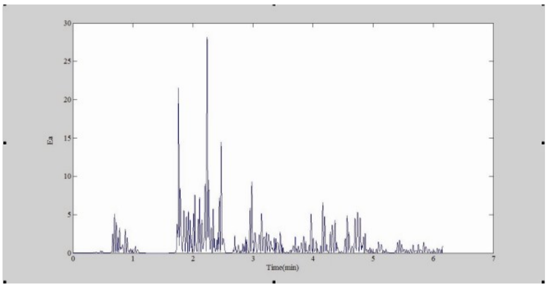


Fig.6- Ea variation with time for Honshu, Japan earthquake 2011 (tsunamigenic).

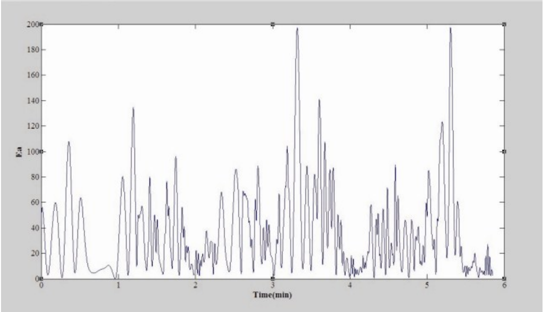


Fig.7- Ea variation with time for East of Kuril island (non-tsunamigenic) earthquake,15thNovember, 2006.

The higher peaks of "Ea" are observed for non-tsunamigenic events in Fig.8 as compared to tsunamigenic. Table 1 shows the values of "max Ea" for different seismograms for higher frequencies. The value of "max Ea" varies from 27.5 to 46 for tsunamigenic events and from 158 to 196 for non-tsunamigenic events. The values are comparatively much higher for non-tsunamigenic events and therefore can be used for identifying tsunamigenesis.
The statistical significance of the 'Max Ea' values for category- I and II (as mentioned in table 1) are checked using standard "t-test".
The "t-test" on category- I and II events are given as follows:

1. H$_o$: $\mu 1 = \mu 2$ ($\mu 1, \mu 2$ represents mean of "Max Ea"for category I and II)
2. H$_1$: $\mu 1 < \mu 2$
$\alpha : 0.05$
3. We reject H$_o$, if t< $t_{0.05}$, where $t_{0.05}$=1.860
Calculation :

$$t = \frac{\overline{X_1} - \overline{X_2}}{S_{x1x2}\sqrt{(1/n1 + 1/n2)}}$$

$$S_{x1x2} = \sqrt{\frac{(n1-1)S^2_{x1} + (n2-1)S^2_{x2}}{n1+n2-2}}$$

$\overline{X_1}$ and $\overline{X_2}$ are samples mean.

Degree of freedom (υ) = $n1+n2-2$

$t_{calculated}$= -27.94
4. As $t_{calculated} < t_{0.05}$, hence we can reject Null hypothesis.

5. Therefore, we can conclude that “Max Ea” value for category I are less in comparison to category II. That is low value of “Max Ea” for Tsunamigenic earthquakes.

This is confirmed by FFT as for frequency range of 0.15-0.35 Hz the normalized amplitude of tsunamigenic earthquake is below 0.1, indicating presence of long period energy (i.e. absence of high frequency energy) as shown in Fig.9.

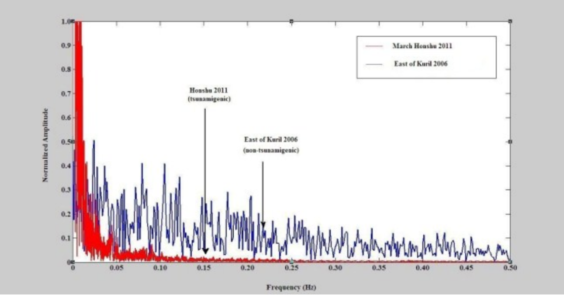


Fig.9- Comparative study on FFT analysis of Great Tohuku, Japan (tsunamigenic) and East of Kuril Island, Russia (non-tsunamigenic) earthquake.

The depleted high-frequency energy nature of the tsunamigenic earthquake may be explained by their large rupture area with large slip and slow rupture speed. The average slip during rupture for tsunamigenic earthquake is usually larger than that for non-tsunamigenic earthquake of the same magnitude.

Conclusions

First few minutes of, Great Tohuku Japan earthquake seismograms and other global tsunamigenic and non-tsunamigenic under sea earthquakes are studied for quick prediction of tsunami. The frequency content of the seismograms and energy content in high frequencies is observed to give tsunami warning. For Great Tohuku, Japan 11th March, 2011, it is observed that wavelet coefficients for frequencies greater than 0.33 Hz (scale below 50) do not show significant energy in the spectrum and confirms tsunamigenic earthquakes. However, significant energy is found in wavelet spectrum of non-tsunamigenic earthquake.In tsunamigenic earthquakes there is absence of high frequencies that is probably due to the large slip and slow rupture. This behaviour is well manifested in the frequency domain and similar characteristics are also observed in fifty such earthquakes. Hence we conclude that for an earthquake whose normalized amplitude value lies below this threshold (0.1) in the frequency range of 0.15-0.30 Hz will have probability of generating tsunami. The method used in this paper is fast and overcome the problems of conventional tsunami warning methods in practical situations.

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