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Prompt identification of tsunamigenic earthquakes from 3-component seismic data

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ABSTRACT

An Artificial Neural Network (ANN) based algorithm for prompt identification of shallow focus (depth < 70 km) tsunamigenic earthquakes at a regional distance is proposed in the paper. The promptness here refers to decision making as fast as 5 min after the arrival of LR phase in the seismogram. The root mean square amplitudes of seismic phases recorded by a single 3-component station have been considered as inputs besides location and magnitude. The trained ANN has been found to categorize 100% of the new earthquakes successfully as tsunamigenic or non-tsunamigenic. The proposed method has been corroborated by an alternate mapping technique of earthquake category estimation. The second method involves computation of focal parameters, estimation of water volume displaced at the source and eventually deciding category of the earthquake. The method has been found to identify 95% of the new earthquakes successfully. Both the methods have been tested using three component broad band seismic data recorded at PALK (Pallekele, Sri Lanka) station provided by IRIS for earthquakes originating from Sumatra region of magnitude 6 and above. The fair agreement between the methods ensures that a prompt alert system could be developed based on proposed method. The method would prove to be extremely useful for the regions that are not adequately instrumented for azimuthal coverage.

1. Introduction

This paper deals with the issue of prompt identification of shallow focus tsunamigenic earthquakes at a regional distance (~2000 km) using seismograms recorded at a single 3-component broad band station. It may be noted that in this article an earthquake is called tsunamigenic if it generates a tsunami (Satake and Tanioka, 1999) while a potentially tsunamigenic earthquake (PTE) is the one which occurs at a fault located near or beneath the sea and may generate a tsunami depending on other conditions. An attempt to identify a PTE as tsunamigenic earthquake with minimum possible resources is very valuable from the point of view of mitigating losses due to local and regional tsunamis originating in poorly instrumented regions of the world. The motivation for doing this exercise stems from the fact that a single 3-component seismogram contains all the information about the earthquake source so as to be used as a quick identifier of a tsunamigenic earthquake. The information content might not be enough to estimate the numerical values of all the earthquake source parameters in practice, but certainly is sufficient to identify its tsunami generation capability. For example, mere presence of high amplitudes of long period surface waves (LQ and LR) in the 3-component seismogram is an indication that source depth is less than about 70 km. Unless it is required to be used in tsunami modelling, this much knowledge of depth might be adequate for classifying an earthquake as tsunamigenic, provided other parameters such as magnitude, focal parameters and epicentral location etc indicate it to be one.

Especially at local and regional distances, a tsunami is one of the most destructive marine natural hazards in the world which causes extensive damage to life and property in a very short duration of time. A 2009 Global Assessment Report (www.preventionweb.net/english/countries/statistics/risk.php?iso=IND) puts the number of Indian population exposed to tsunami hazard as more than a million. Average annual loss due to tsunami is estimated to be 19.14 million USD. Tsunamis are generated by large-scale vertical displacement of ocean water due to tsunamigenic earthquakes, submarine volcanic eruptions and landslides. Among these, the tsunamigenic earthquakes are the main causes which have resulted in large number of notaiceable tsunamis in different parts of the world. In the Indian Ocean, Sumatra region is one of the most prominent sources of tsunamis and is located at regional distance

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from eastern Indian coast, Sri Lanka and many other habitable islands. A fully operational tsunami early warning centre called Indian Tsunami Early Warning Centre (ITEWC) is functioning at Hyderabad, India to issue tsunami advisories in this region (www.incois.gov.in). In general tsunami early warning system for a given region comprises of a real time network of several seismic stations, Bottom Pressure Recorders (BPRs), tide gauges and 24×7 operational data centre to monitor tsunamigenic earthquakes and propagation of tsunami waves in the ocean for deciding on issuing of advisories.

Present methods of tsunami early warning (Titov and Gonzalez, 1997) essentially involve modeling of tsunami generation process by earthquakes, propagation of tsunami waves through ocean waters and inundation length, run-up height simulation in the affected coastal regions. Among these processes the tsunami generation stage may be modeled by solving hydrodynamic equations with boundary conditions at the ocean floor which corresponds to static displacements caused by earthquake sources (Okal, 1982; Comer, 1984). These boundary conditions (fault length, fault width, average static displacement) may be evaluated for an earthquake source from its magnitude and focal parameters. Okada model (Okada, 1985) which models sea surface deformation due to shear and tensile faults in half space is one of the most widely used techniques of modeling tsunami generation by earthquakes. However, in the initial few minutes of the earthquake origin, only magnitude and hypocenter parameters are available normally. The focal parameters and seismic moment which generally require azimuthally distributed multi station data become available much later ($\sim$30 min). This much time may be prohibitively long for nearby coastal regions. Hence, the fault parameters required for modeling tsunami generation (boundary conditions) are evaluated for worst case scenario (45° dip and 90° slip). In fact to avoid time loss due to model simulation, most of the tsunami warning centers develop and maintain a pre-computed data base of the worst case scenarios for given regions and search them on the basis of estimated hypo central location and magnitude. Empirical relations between moment magnitude and fault parameters (Papazachos et al., 2004) are also used at some regional distances. Thus the first alert of an impending tsunami by most of the tsunami warning centers is based mainly on simulation results. Later when actual focal parameters become available and tsunami generation is confirmed or denied by BPR and tide gauge data, these warnings are upgraded or downgraded. Besides demonstrating the use of ANN in tsunami warning this paper, by virtue of inclusion of focal parameters in the form of seismic phase amplitudes, is expected to support present methods by reducing false alarms.

In view of the above, it is always desirable to use seismic data of only a few available stations (minimum requirement being data from a single 3-component station) to provide the decision of an impending tsunami as early as possible. The present paper attempts to explore an alternate and reasonably effective route of mapping moment magnitude (M_w), location and root mean square (rms) seismic phase amplitudes in the recorded velocity seismogram directly to binary decision space of PTE category (*CAT*) (viz. Tsunamigenic (T) or Non-Tsunamigenic (NT)). It may be noted that M_{wp}, a good estimate of moment magnitude M_w, can be obtained from P phase rather quickly (Tsuboi et al., 1995, 1999; Tsuboi, 2000). As a further investigation the duration amplitude procedure was proposed to estimate duration based moment magnitude, M_{wpd} (Lomax and Michelini, 2009). These estimates are typically available prior to the arrival of LR phase. Relying mainly on excellent nonlinear mapping capability of an artificial neural network (ANN) trained from the seismic data of past tsunamis the technique may be used at any tsunami-source station pair of the world and is expected to be very effective especially in poorly instrumented regions. Since the tsunami potential of an earthquake is best estimated using focal parameters, the paper also formalizes the underlying theory relating seismic phase amplitudes to focal parameters and in turn water volume to corroborate the validity of the proposed method. Tacit assumption made here is that the estimate of water volume displaced at the tsunami source would give a fairly accurate classification of earthquakes. For the present study, Sumatra is considered as the region of tsunamigenic earthquake source and seismogram recordings at PALK (Pallekele, Sri Lanka) station of IRIS (Incorporated Research Institutions for Seismology)–IDA network operated by University of California-San Deigo is used as reference data for the classification of a PTE that may generate appreciable tsunami at regional distances from the source.

2. Method

For investigating tsunami generation capability of earthquakes from Sumatra region (Fig. 1) using single 3-component seismograms recorded at PALK station, a new method is proposed here which directly maps the moment magnitude (M_w), location and root mean square amplitudes of seismic phases to earthquake category using an ANN. Fig. 2 however, pictorially presents two alternate routes (1) direct mapping using ANN-I and (2) indirect mapping using ANN-II via estimation of water volume. Both the techniques involve computation of rms amplitudes of P, S and LR phases besides estimation of location (i.e., epicentral distance and back azimuth) and moment magnitude. A typical seismogram recorded at PALK station is shown in Fig. 3. The key idea behind this approach is that for a given source-station path, the seismic phase amplitudes are function of source strength (magnitude) and focal parameters. Hence a hypothesis may be formally stated as below.

Hypothesis–I: Seismic record of a single 3-component broadband station contains sufficient information required for categorizing a PTE and hence azimuthal coverage of stations may not be necessary.

The proposed hypothesis is tested by formalizing the relationship between seismic phase amplitudes recorded by a 3-component station and focal parameters of the earthquake in the following subsection.

2.1. Mapping of seismic phase amplitudes to source parameters

The force system causing an earthquake is modeled as a double couple point source which gives the radiation pattern of P waves as a compressional and a dilatational lobe in alternate quadrants (Aki and Richards, 1980). The polarity of S waves alternates in a similar way. However, S waves have highest amplitude along the nodal planes orthogonal to those of P waves. Given a fault geometry, besides P and S waves, there could be other phases present in the recorded signal. Each of these phases is generated by interaction of P and S waves taking off from the source at unique angles. For a given source-station path, as the fault geometry changes, take-off angles of P and S waves change, thereby generating a seismogram at the receiver with a distinctly different set of phase amplitudes. Conversely a given set of phase amplitudes at the receiver at a fixed azimuthal location with respect to a fault will correspond to unique fault geometry and it would be possible to estimate source parameters from them, provided a large number of phases are included in the set.

With this background, the far field rms displacement amplitudes of seismic waves (Aki and Richards, 1980; Kanamori and Given, 1981; Lay and Wallace, 1995) may in general be written as

$$\left|u^i(\mathbf{x},t)\right| = K_1 M_0 \gamma^i_{nl}(\varphi_s,\delta,\lambda), \quad i = 1,2,\dots n \tag{1}$$