Crowdsourcing an Earthquake early warning system for the Indian Subcontinent

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ABSTRACT

Earthquakes are potentially very destructive natural events. The risk from earthquakes is aggravated because they are unpredictable and can cause tremendous loss of life and property within seconds, particularly in dense urban settings. We present our ongoing work to develop a comprehensive earthquake early warning system (EEWS) for the Indian subcontinent. The impetus for this work comes from the fact that India has just 82 seismic stations for a land area of about 3.2 million sq. km, with no dedicated EEWS, plus low-cost accelerometers are now easily available, and smartphones have a deep penetration. The planned system will use a network of mobile smart phones and stationary low cost MEMS based strong motion sensors. The main components of this project are: creating a high-density network of low-cost sensors, real-time transmission of data, algorithms to analyze ground shaking data, compute ground motion characteristics, and determine if the source of shaking is an earthquake.

INTRODUCTION

As per the Center for Seismology of the Indian Meteorological Department, about **57%** of the land surface in India is vulnerable to seismically induced ground shaking. As per a report in Times of India, citing a World Bank and United Nations report, around 200 million city dwellers in India will be exposed to high risk from storms and earthquakes by 2050 (Times of India 2011). Every major earthquake kills thousands of people in India. Figure 1 below shows the estimated locations of earthquakes in the Indian subcontinent over the last two centuries.

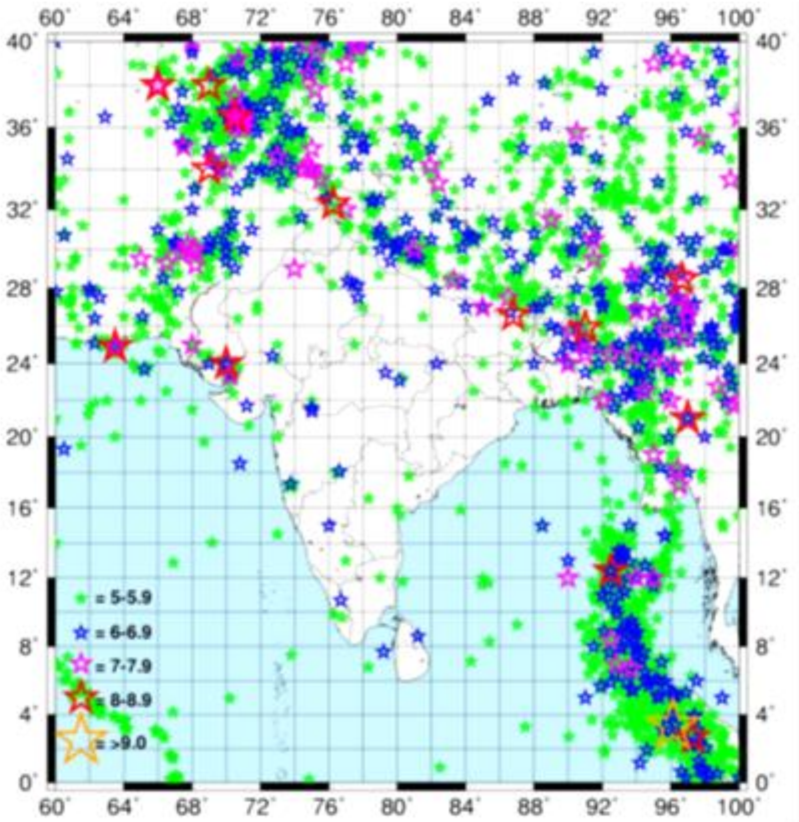


Figure 1. Distribution of Earthquakes (M>5) in the Indian Subcontinent (1820 to 2011) [Source: Indian Meteorological Department]

Earthquakes. As the tectonic plates drift across the earth's surface, the two blocks forming the opposite sides of a fault move by a small amount; this motion elastically strains the rocks near the fault. The earth's crust is elastic, but only to a point. When the stress becomes larger than the frictional strength of the fault, the frictional bond fails at its weakest point, called the hypocentre, which is deep below the surface of earth. The rupture rapidly propagates along the surface of the fault, causing the rocks on opposite sides of the fault to begin to slip past each other. The elastic energy stored in the rocks is released as seismic waves. The seismic waves radiate from the hypocentre in all directions producing the earthquake. Seismic waves are of two types: P-waves or primary waves, and S-waves or secondary waves. P-waves are compression waves, which travel faster than S-waves, but carry a relatively small amount of energy. S-waves are shear-waves which are slower, but contain most of the energy released by an earthquake and bring a stronger shaking of the earth's surface causing much more damage.

By monitoring the build-up of strain between earthquakes, seismologists know that many areas of the crust are close to failure, but the detailed structure of the faults deep below the surface also plays an important role in both the nucleation and propagation of earthquake ruptures. For this reason, most seismologists do not believe that it is possible to create a system capable of predicting the magnitude, position and time of a future earthquake (Allen 2011).

But, the difference in travel speeds of P and S waves can be exploited to provide some advance warning. Work done by the United States Geological Survey (USGS), the Japan Meteorological Agency (JMA), and some other leading institutions has demonstrated the feasibility of earthquake early warning (**EEW**) systems that can issue a warning before the arrival of the damage causing S-wave.

EARTHQUAKE EARLY WARNING

Unlike earthquake prediction, earthquake early warning systems are considered to be an achievable goal. The term “earthquake early warning system” (EEWS) is used to describe real time earthquake information systems, which have the possibility of providing a warning before the ground starts shaking significantly. This is possible by detecting the P-wave radiating from an earthquake rupture and estimating the position and magnitude of resulting ground shaking that will occur later. The warning time available depends on the relative distance between the earthquake source, the locations of the sensors in EEWS network, and the area at risk.

Strong ground shaking is caused by shear waves (S-waves), which are appreciably slower than P-waves. Therefore, a system which detects and identifies P waves and transmits a warning using an electromagnetic signal can provide early warning. Thus, depending on the distance of a strong earthquake from the endangered area, transmission of information and real-time analysis of the first P-wave may provide warnings which range from a few seconds to several minutes before the strong ground shaking starts. With such a warning, people can evacuate buildings, authorities can shut down critical systems such as electrical generation/transmission stations, nuclear power generation plants, and gas pipelines, and suspend service on vulnerable transport systems before severe ground shaking starts.

EEW around the world. EEW systems are in place in a few countries, namely, Japan, Mexico, Taiwan, Turkey, and Romania. China, Italy and the United States (with California in the lead) are developing EEW systems as part of a real-time seismic system with the aim of reducing the damage, costs, and casualties resulting from an earthquake (Allen 2009, Strauss 2016).

Mexico is home to the oldest EEW system in the world. They started working on it in 1991 with Mexico’s strong-motion accelerometer network, which monitored large subduction zone earthquakes near the western coast and alerted residents of Mexico City that heavy shaking was on its way (Suarez 2009).

Japan started working on an EEW system after the great Hanshin earthquake of 1995. The system became active in 2007. The Japanese EEW system successfully alerted several million people near the epicenter, providing 15–20 s of early warning, for the 2011 M 9.0 Tohoku-Oki earthquake and tsunami (Fujinawa 2011).

The U.S. Geological Survey (USGS), in partnership with the University of California at Berkeley, the California Institute of Technology, and the University of Washington, created an EEW initiative called ShakeAlert (Strauss 2016). The

ShakeAlert system incorporates existing sensors from the California Integrated Seismic Network and the Pacific Northwest Seismic Network and sends alerts to some test users which include the BART, Boeing, Intel and the cities of San Francisco and Los Angeles. It is currently an end-to-end prototype, and work is being done towards converting it to a robust system. Further details regarding the system can be found at (http://www.shakealert.org/.) Figure 2 depicts earthquake sensor density in California and Japan.

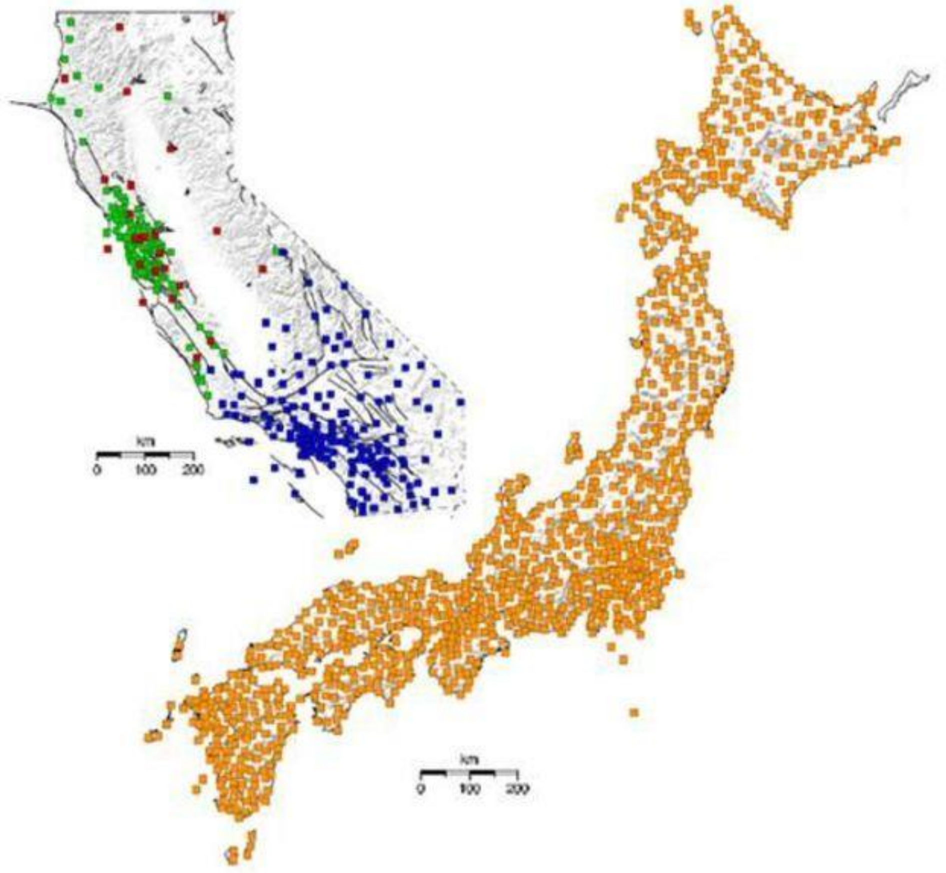


Figure 2. Earthquake sensor density: California versus Japan [Source: USGS]

Seismic Infrastructure in India versus that of California and Japan. The Centre for Seismology, Indian Meteorological Department (IMD) under Ministry of Earth Sciences is the nodal agency of the Government of India dealing with various activities in the field of seismology. As of 2013, they operate and maintain a seismological network of 82 observatories, which monitor seismic activity, and archive and estimate the source parameters such as the magnitudes and epicenters of earthquakes. Additionally, they maintain a network of 17 real time seismic monitoring stations dedicated to issue tsunami warnings. Figure 3 is a seismic station map for India.

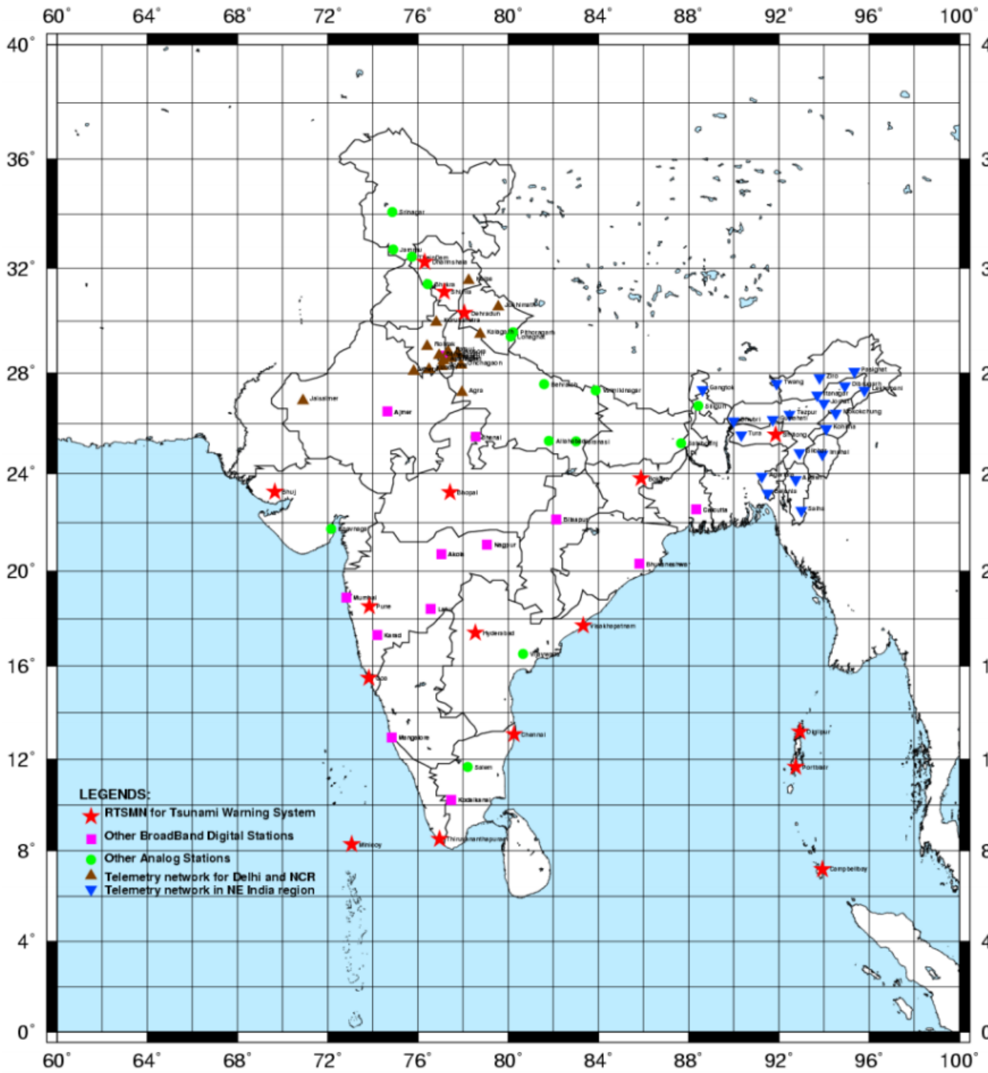


Figure 3: Seismic station map for India (Source: Indian Meteorological Department)

Table 1 Comparison of Seismic Station Density [6][9]

	California	Japan	India
Number of stations	377	1089	82
Area (1000 sq km)	423	377	3200

Research done by the Berkeley Seismological Laboratory (BSL) suggests a minimum seismometer density of one seismic station for every 400 sq km to minimize the response time for EEW systems and to reduce the effects of blind spots. This recommended density results in a minimum of 2,560 stations for India. Even if we cover just the zones corresponding to moderate risk and higher (zones 3, 4 & 5 per IMD Classification), that is still 57 % of India's land mass, resulting in a minimum target of 1280 seismic stations.

EEW in the age of the internet of things. Significant efforts have been made at CalTech and UC Berkeley to crowd source data to generate warnings for California. These studies have demonstrated the feasibility of the use of low cost MEMS accelerometers in detecting earthquake P waves. Allen et al. (2016) report that the MEMS accelerometers in most smartphones are sensitive enough to detect seismic waves originating from an earthquake of magnitude 5 or larger, at distances of up to 10 km, in the frequency range of 1 to 10 Hz (the range that causes the most damage). The Berkeley seismological laboratory has tested smartphones which comes with MEMS accelerometers for their use in EEW systems and is currently testing an EEWS proof of concept called MyShake (Allen et al. 2016).

Mobile cellular technology has seen exponential growth throughout the world in the last few years with increasing global access to 3G / 4G. India has not been an exception to this. There has a tremendous increase in the mobile cellular coverage in India with increasing number of 3G/4G connectivity. Figure 4 below depicts cellular coverage in the Indian subcontinent. Figure 4 has been compiled using data from OPEN SIGNAL (https://opensignal.com/coverage-maps/), the green / red spots on the map depict regions with 2G/3G/4G cellular connectivity. The solid black line demarcates the edge of cellular connectivity in the lower and middle Himalayas. The Highlighted region corresponds to regions that are classified as intensity VII or above on the Modified Mercalli scale as per Prevention Web (http://www.preventionweb.net/files/3285_UNISDRAsiaPacificRegional2.pdf).

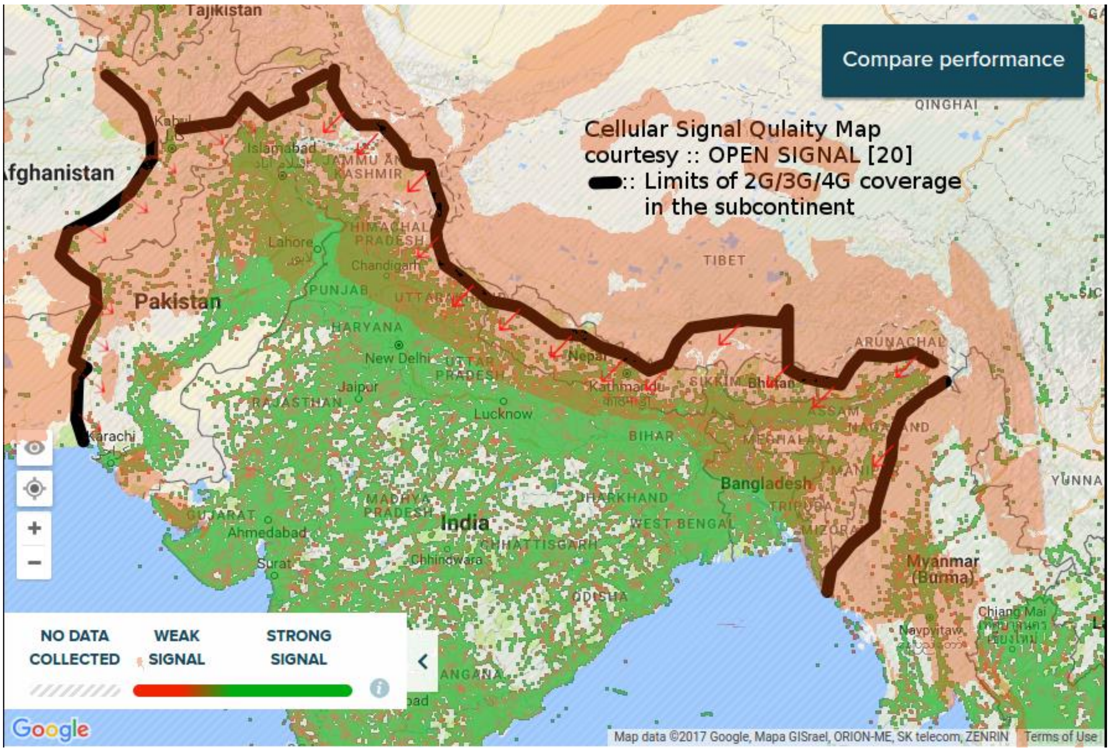


Figure 4. Cellular coverage in the Indian subcontinent

PROPOSED EEWS

The proposed EEW system is tailored to the requirements of the Indian subcontinent. It has three different components: (i) data collection units consisting of low cost sensors and an android app for collecting and sending accelerometer data; (ii) algorithms for extracting preliminary features from the seismic shaking data by on-board processing; and (iii) a central server for extracting secondary features and running algorithms to calculate the magnitude of the earthquake.

We have developed two different types of network devices which can be scalable**.**

1) Low cost fixed cellular nodes that are fitted out with a MEMS Accelerometer a magnetometer, a GPS unit, a DSP capable microcontroller and a cellular GPRS/3 G /4G radio system. These modules will be fixed on the walls/ceiling of the houses of the general public. These will record data and after primary classification send it to the server for further processing.

2) Smartphone based mobile nodes, which use an app through which the accelerometer data can be recorded and send to server for processing, communicate with other mobile nodes in their proximity, and transmit a warning when an earthquake has been detected.

Table 2. Minimum Specifications for an EEW node

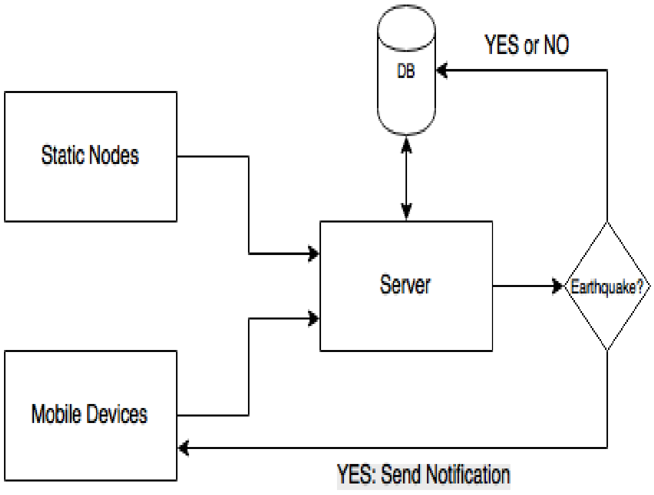
Sensor(s)	Tri axial MEMS Accelerometer, GPS , Magnetometer
Accelerometer Sensitivity	±3g
Frequency Response	0.7 Hz to 2.5kHz
ADC Resolution – minimum	12 bits
Computational spec.	32-bit micro controller - w/ integrated FPU (DSP cores) & RTC - x86/ ARM
Radio(s)	3G / 4G LTE - Cellular (Indian bands)
Secondary Storage	On board Flash to archive daily data

Both classes of devices will record strong motion data from their accelerometers, run an algorithms (discussed below) to extract wave features which will be used to detect the arrival of a P-Wave with the help of a classifier.

On detection of P-Wave or a P-like Wave (False Positive), the device will send the data to the server for further processing and computation over a cellular 3G / 4G IP layer.

The central server will extract some secondary features and, based on those secondary features, it will run an algorithm to calculate the moment magnitude of the earthquake. The server will additionally use the incoming P-wave to estimate the epicentre and hypocentre of the earthquake and will decide on whether to release a warning or not.

The devices upon receipt of warnings from the server will notify their users to initiate emergency response procedures.



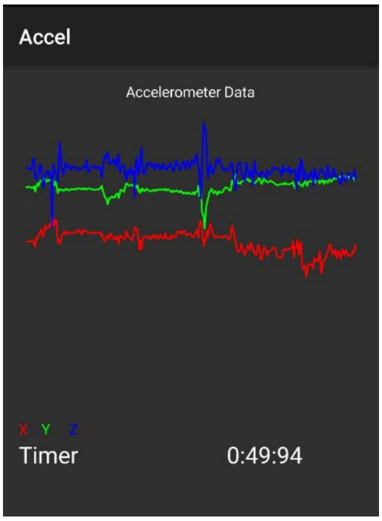


Figure 5. An overview of system topology

Figure 6. Smartphone app

FINDINGS

We have already assembled and tested some stationary modules, and built an Android application for recording and transmitting data. As discussed below we generated some shaking data and extracted features from it to classify it and differentiate it from other waves – this serves as the initial testing phase,

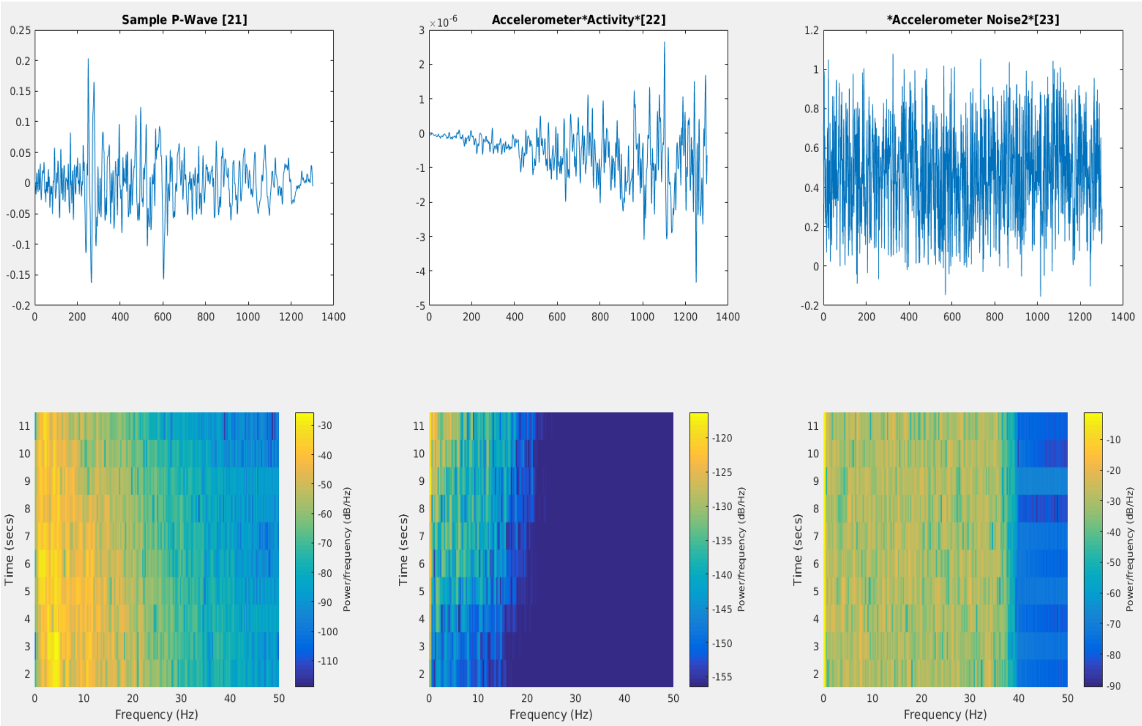
Feature extraction and P wave picking. We have developed a mobile application that streams accelerometer recordings to a server where features are extracted and classified in real time. The features we are currently studying are the power spectral density for the 0 – 10 Hz range, the peak ground acceleration, velocity and displacement.

Dataset generation. This is an essential part of developing machine learning models to solve classification problems. We developed two datasets that are labelled as follows:

1) *P Wave*: We used accelerograms from the PEER NGA West 2 database through the P phase picker (Kalkan, E. 2017). We sampled a 10 second window around the occurrence of the same and ran it through our feature extraction module. The outputs were appended to the seismic record database being developed at SNU.

2) *Not P wave*: We used a variety of accelerograms most notably from the USC Human activity database records (USC–HAD).Other Sources include band limited random noise. These records were randomly sampled windows and extracted features.

Figure 7 below shows the power spectral density of different waves. The first, labelled (A), is a waveform of an earthquake, the second, labelled (B), is randomly sampled activity, and the third, (C), is band limited random waveform.



A **B** **C**

Figure 7 Power spectral density of different waves

[**A**. P-Wave identified by the PEER P phase Picker ; **B**. Human Phone use activity randomly sampled (USC - HAD); **C**. Band limited random waveform]

P Wave detection. For the preliminary analysis, we used a linear classifier (from python's scikit-learn library) on datasets generated from California. We got an accuracy of 88.78%. We also tried using decision tree classifier and AdaBoost classifier, again from python's scikit-learn, whose accuracy for the same dataset turned out to be 90.22% and 92.21%, respectively. While we anticipate a drop in accuracy with the incorporation of locally sourced earthquake data, we believe our polling algorithm will make up for some of the shortcomings at this stage. Additionally, Neural Network models are being explored. ("scikit-learn: machine learning in Python — scikit-learn 0.16.1 documentation" 2017)

Event polling and earthquake EEW. When the fixed and mobile sensor modules detect and classify the pattern of ground shaking as a p wave, they will notify a collection of distributed polling servers. Each server will be running pattern detection and classification algorithms. When there is an overall positive classifications in a given time window, and on the basis of secondary parameters, each server will decide whether to issue an earthquake warning in the region it caters to, and will also notify adjoining region warning arbitrators.

Algorithm to find the magnitude. For the current phase of our work. We have chosen to use the τ_c-P_d on-site warning algorithm developed by Kanamori (Kanamori 2005). This algorithm is considered robust and has been tested by other researchers, including some real time testing by the California Integrated Seismic Network (Hauksson et al. 2006). The algorithm is based on single sensor observations using two parameters: period parameter τ_c, and high-pass filtered displacement amplitude P_d. Both parameters are determined from the vertical components of velocity and displacement data, $\frac{du}{dt}$ and u. The algorithm uses the first three seconds of the recorded P-waveforms. The period parameter τ_c, is computed using the following equation:

$$\tau_c = \frac{2\pi}{\sqrt{\left[\int_0^{t_0}\left(\frac{du(t)}{dt}\right)^2 dt \ / \int_0^{t_0}(u^2(t)dt\right]}}$$

Previous studies have determined empirical relationships between τ_c and the moment magnitudes Mw, and between P_d and the peak ground velocities (PGV) of the observation sites (Kanamori, 2005; Wu and Kanamori, 2005). These observed and estimated values of PGV can be transformed into Modified Mercalli Intensity (MMI) scale using empirical relationships developed by Wald et al. (1999). So with the help of the equation and the empirical relationship we can get the magnitude of the earthquake.

DISCUSSION AND CONCLUSION

In this age of information, quick connectivity and low-cost sensors, development of earthquake early warning system has not only become possible but also economically viable. The project discussed here is inspired by the technological advances in multiple fields: networking, data processing, sensor design, mobile computing, and real time seismology. In the event of a potential disastrous earthquake (magnitude 5 and above) originating in the foothills of the Himalayas, a functional EEW system can help in saving hundreds, perhaps thousands, of lives and preventing thousands of people from getting injured. This project will also be an important step in getting good quality ground motion data from earthquakes originating in northern India and beyond.

We believe that an earthquake early warning system such as the one we propose here has great potential not only in saving lives but also in mitigating damage to critical infrastructure. Such a system will be a critical part of India’s sustainable development goals, to mitigate the impact of natural disasters, and develop resilient, sustainable infrastructure systems.

For an EEW system to be truly functional and viable in the long run, buy-in is needed from the public and from the government. As such, collaboration with local and regional municipal authorities will be a critical component of our work as we move forward on developing an earthquake early warning system for the Indian subcontinent.

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