DEVELOPMENT OF THE EARTHQUAKE PREDICTION TECHNIQUES IN THE CONTEXT OF DISASTER MITIGATION

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Abstract: *The paper examines the evolution of earthquake prediction techniques in the context of disaster mitigation. The first ever attempt made in this perspective was the keen observation of anomalous behavior of animals prior to the occurrence of an earthquake. The China has, recently, successfully exploited this historical practice of predicting earthquakes to explore its potential of predictivity. It has established an efficient monitoring set-up for the keen observation and recording of anomalous behavior of animals in its earthquake-prone zones. The same practice has been taken on by some other countries as well. The development of modern techniques, like, GPS total station, seismic array technology, ASTAR and SRTM satellite images, are providing real time facility to precisely monitor the strain distribution in lieu of stress accumulation in active seismic zones. Based on acquired data from the old historical records, paleoseismology and modern techniques, like, identification of earthquake precursors, seismic gaps' perception, delineation of zones and levels of risk of an area, successful attempts have been made to perceive a few probabilistic forecasts of earthquakes occurrence in the perspective of disaster mitigation. By recognizing the focal importance of earthquake precursors' identification the investigations executed in the field of seismology have shown that the elusiveness of earthquake precursors is a major cause of failure to predict some earthquake event reliably. The newly developed seismic array technology is a consistent tool for the identification of these precursors in any region through its vigilant seismic monitoring and facility to anticipate the earthquake incidence. In the light of present review it is concluded that no technique, to date, could has been developed, capable of facilitating a clear-cut forecast of an earthquake. However, in view of pace of advancement in modern technology reliable earthquake forecasts might, most likely, be conceived in near future.*

Key words: Earthquake prediction techniques, development, disaster mitigation

INTRODUCTION

An earthquake is a manifestation of vigorously powerful natural processes resulting in spontaneous rock slip over a fault plane and shaking of parts of earth and causing tremendous loss of life and materials within seconds. The sudden release of energy takes place due to the sliding of a part of the Earth's crust along a fault, e.g., along the Main Boundary Thrust (MBT) near Kohat, Islamabad and Balakot-Pakistan during the rattling of Kashmir Earthquake, 2005. The frequency of occurrence of earthquakes of different magnitude in Pakistan and South Asian region has alarmingly increased during the past two decades (IUCN, 2006 and WHO, 2005). To stop an earthquake is beyond the control of man even in this modern age. However, its forecast or prediction is possible to some degree. A plenty of ways and techniques have been developed to foresee the happening of an earthquake. The earthquake prediction can play an important role in the disaster preparedness and eventual risk reduction. If any forecast is there, even that of only few hours before the occurrence of an earthquake, it might become instrumental to reduce the vast devastation incurred by it or at least material and life losses could be avoided to a great extent. This paper presents a review on the evolution of earthquake prediction techniques and developments made in this context. These techniques are applied for safe time prediction of earthquakes in the preview of disaster preparedness and mitigation.

It is estimated that in the last five centuries more than seven million people died and many more millions humans saw their physical and economic resources devastated (Nizami, 2006, Tehami, 2006, Plummer, *et al.*, 2000, Bolt, 1999, Hamblin and Christiansen, 1998, Bolt, 1993 and Skinner and Porter, 1989). That is why man has remained constantly in search of any technique/s or device/s to forecast these events of destruction since several centuries in his life and limb saving pursuit. During the 20th century and particularly in last two decades (1990-2010) a number of modern devices, instruments and techniques, like, GPS total station, teleseismic recording seismometer, seismic array technology, ASTAR and SRTM satellite images, have been developed to precisely monitor the stress and strain distribution and accumulation in lieu of plate movements in active seismic zones or in other words in earthquake prone parts of the world (Roach, 2004, Plummer, *et al.*, 2000, Frankel, *et al.*, 2000, Clement, *et al.*, 1999, Bolt, 1999, Hamblin and Christiansen, 1998, Bolt, 1993 Skinner and Porter, 1989 and Yang, 1982). Based on acquired data from these modern equipment and techniques the high-to-low risk seismic zones could be delineated and prediction of occurrence of earthquakes is solicited in the perspective of disaster preparedness and mitigation. A more reliable and better earthquake forecast put the retrofitting projects on priority and launch enhanced preparatory campaigns for the general public in the medium to high risk zones of earthquake occurrence.

FORECAST

As far as the earthquake forecast is concern there are two possibilities. The first one is that of "expected forecast" and the second possibility is that of "real time and precise prediction". For a successful prediction the requisite data would include time frame, magnitude and location of an earthquake. Techniques to measure magnitude and location of earthquakes have improved dramatically in last 60 years. A hallmark development in this respect was the establishment of Worldwide Standardized Seismograph Network (WWSSN) in 1963 by USA (Bolt, 1993). This network is now equipped with much upgraded seismographs and about 1000 observatories distributed all over the world (Bolt, 1999).

This network allows know accurate time, location and magnitude of earthquake around the world. Moreover, a number of government-sponsored programs have been launched by USA, Japan, China and former Russia, focusing on various monitoring systems along major fault zones to investigate stress and strain variation and their accumulation at any location (Bolt, 1999).

The strategies of earthquake prediction are formulated on the base of following parameters: historical records, paleoseismology, earthquake precursors, seismic gaps and risk levels. Typical precursors, like, short-term and long-term changes in earth prior to occurrence of an earthquake are particularly sought for delivering a reliable forecast (Harrington and Shou, 2004, Plummer, et al., 2000, Frankel, et al., 2000, Clement, et al., 1999, Bolt, 1999, Hamblin and Christiansen, 1998, Bolt, 1993 and Skinner and Porter, 1989). Laboratory and field studies of road behavior before, during and after major earthquakes are conducted to gather data for further use in the forecasting purpose.

According to Plummer, et al., (2000) and Bolt (1999) Chinese have successfully predicted several earthquakes. They, however, failed, also, to predict in few cases, for example, Tangshan Earthquake of 1976, which engulfed 2, 42,000 lives and incurred tremendous damage to infrastructure everywhere in the victim area (Plummer, et al., 2000, Bolt, 1999, Hamblin and Christiansen, 1998, and Bolt, 1993).

ANOMALOUS BEHAVIOR OF ANIMALS

The historical practice of predicting earthquake from the keen observation of anomalous behavior of animals prior to the occurrence of earthquake was the first ever human attempt in this context. According to the Nanning's Earthquake Bureau (2006) China has recently exploited successfully its potential of earthquake predictivity in a number of events and has established a set-up to keenly monitor the anomalous behavior of animals in its earthquake prone zones (Nelson, 2004 and Kirschvink, 2000). Modern examples of the same practice from some other countries are present as well (Plummer, et al., 2000 and Hamblin and Christiansen, 1998).

Snakes

It has been noted that the animals, that pass winter in the underground burrows, like, snakes and frogs, drastically came out suddenly prior to the occurrence of an earthquake. On the basis of these extra ordinary animals' behavior it is predicted that probably an earthquake is going to hit the area. Of all the creatures on Earth, snakes are, perhaps, the most sensitive to earthquakes. When an earthquake is about to occur, snakes will move out of their nests, even in the cold of winter. If the earthquake is a big one, the snakes will even smash into walls while trying to escape. Their anomalous movements due to reacting strangely towards an earthquake, which might occur within few days, is used as a key to help predict earthquakes. Such an abnormal reaction of the "Head-Banging" snake (Plate A, Fig. 1) assisted in devising an "Earthquake Prediction System" in China (Earthquake Bureau, Nanning, Guangxi Autonomous Region, Southern China, 2007).

According to the Earthquake Bureau this newly developed system relies on the behavior of snakes to make earthquake predictions and is based on their "Natural Instinct". Snakes can sense an earthquake originating from a focus that is around 120km away. This crawling creature is, also, capable to sense an earthquake 3 to 5 days before it rattles an area. The Chinese researchers found that the snakes are relatively more sensitive to the probable underground changes as this creature lives in burrows. As mentioned earlier the China has developed an "Earthquake Prediction System" based on the brilliant combination of natural instinct of snakes and modern technology. The development of aforesaid "Earthquake Prediction System" took place just after two days as backdrop of two quakes, which struck off the neighboring Taiwan.

In the same line of predicting earthquakes a few useful experiments of the Chinese scientists are notable and have the potential to make an absolute earthquake forecast. It is interesting to share here that prior to the Earthquake of the Sichuan Province in August, 1976, the Chinese scientists observed that the snakes had left this area and had moved to safe locations before the occurrence of this earthquake. Likewise, the snakes rushed out of the area before the Tang Shan Earthquake (July, 1976) struck this region. These crawling animals managed to gather in a ditch 40km away from the area (Earthquake Bureau, Nanning, Guangxi Autonomous Region, Southern China, 2007).

Birds

It is commonly reported that before any high magnitude earthquake the birds escape out of their nests and fly here and there in distress. The crows unusually gather on trees and make very loud and awkward caw. Scientists think that the 6th sense of animals and birds works quickly on these occasions and they smell the expected danger earlier than humans. It is hoped that the further observations, like, specially noting the abnormal actions and movements of birds and animals, success could be made in the absolute forecast of an earthquake through this technique. According to Nizami (2006) the birds and crows flew in a state of horror and horridness on Oct. 16, 2005 in Muzaffarabad, Azad Jummu and Kashmir-Pakistan round about at 9.30am (local time). The sudden hue and cry, particularly, of crows was noticed by everyone. Approximately after 2 hours an earthquake of magnitude 5 (Richter Scale) struck the already devastated premises of the Muzaffarabad city.

Frogs

It is well known observation that certain animals, for example frogs, could sense even micro-tremors prior to an earthquake and have ability to react to underground minute water movements. According to Mui (2008) on May 5, 2008, many Chinese locals noticed thousands of frogs on the move in Wenchuan County. They were seen traveling without fear of traffic as they crossed streets in mass floods (Plate A, Fig. 2). On Monday, 12th May, 2008 a 7.8 magnitude earthquake occurred near Wenchuan County, Sichuan province, central China region and killed nearly 10,000 people (Mui, 2008).

GROUND WATER LEVELS

According to Nizami (2006) an earthquake prediction was made at least 6 hours before an earthquake event in 1978 on the basis of an extraordinary physical phenomenon observed in the Central Asian states (Ex-Soviet Union). A monitoring team of scientists noted that the level of water suddenly dropped in the wells in this region. The prediction strongly proved to be true as right after 6 hours an earthquake hit this area. This change in the level of water in wells is actually a function of changes in the subsurface fracturing and structural modifications due to creeping variations in seismic stress and strain.

UNUSUAL ACCUMULATION OF ENERGY

Change in rock volume (dilatancy) is caused by high pressure due to stress accumulation, which produces numerous small cracks and fractures in rocks prior to failure. As a result numerous small magnitude earthquakes occur in the area.

In 1986 Japanese scientists noted unusual physical changes during the study of a fault zone. Based on this evidence of unusual accumulation of energy (stresses) on this fault zone they perceived that an earthquake could occur at any time in next few days on the sudden slip of fault blocks. A deep well was drilled on this fault line and a large amount of water injected into it. After a few days the earthquake really occurred, however, with minor jolts (Bolt, 1999 and 1993 and Sawkins, *et al.*, 1978). With this precautionary measure a big earthquake was avoided by converting it into a smaller one. In fact water lowered the resistance of fault blocks and upon release of energy these layers slipped forward slowly and stopped when the force of acceleration and its energy were balanced (Bolt, 1999 and 1993 and Sawkins, *et al.*, 1978). This successful experiment suggests that the monitoring of such unusual physical changes on active fault lines might prove useful for earthquake prediction and as well as for disaster mitigation.

COMBINED MONITORING OF CHANGES

The Chinese scientists made an earthquake prediction on the bases of combined monitoring of changes, like, changes in land elevation, in ground water levels, widespread observation of peculiar animal behavior, and recording of many foreshocks in the Yingkou-Haicheng region during the preceding months and finally noted an unusually increased foreshock activity. The government relied on the work of scientists and issued an evacuation warning for the Haicheng area just one day before and an earthquake of M 7.3 (Richter Scale) astonishingly rattled this area on February 2, 1975. So it proved to be a successful earthquake prediction. This evacuation is credited with preventing 120,000 injuries and fatalities (Nizami, 2006).

Plate A

Fig. 1 Photograph showing the "Head-Banging" snake. It assisted in devising "Earthquake Prediction System" in China (Source: Earthquake Bureau, Nanning, Guangxi Autonomous Region, Southern China, 2007).

Fig. 2 Photograph showing a 'frog flood' that occurred two days prior to the devastating earthquake of May 2008 in the Sichuan Province of China (Mui, 2008)

MODERN PREDICTION TECHNIQUES

On the basis of historical records, paleoseismology, identification of earthquake precursors, seismic gaps perception, delineation of zones and levels of risk of an area some successful attempts have been reported in literature to make the most probable prediction of earthquake of even magnitude going to hit that area (Nelson, 2004, Harrington. and Shou, 2004, Kawasaki, 2004, Press and Siever, 2001, Plummer, *et al.*, 2000, Bolt, 1999, Hamblin and Christiansen, 1998 and Bolt, 1993). The seismologists have finally recognized the focal importance of earthquake precursors' identification for the reliable prediction of earthquakes in the light of perception that the elusiveness of earthquake precursors is a major cause in the failure to predict earthquakes.

During the last few years in the light of research work carried out on earthquake prediction, the American scientists have proposed an idea that in the probable area of occurrence of earthquake, the precursors of seismic waves in the rocks of that area increase unusually (Nelson, 2004). By monitoring these unusual variations a probabilistic forecast of an earthquake could be made.

According to Nelson (2004) earthquake and electromagnetism are related closely. Mian (1989) reached on the same conclusion on the basis of his research work executed in the University of Pennsylvania and Philadelphia, USA that there exists a definite relation between earthquake and these waves. According to Mian (1989) this relationship can prove to be a successful method of earthquake prediction. Several days prior to the occurrence of an earthquake, the frequency of electromagnetic waves is increased than that of normal days. This phenomenon continues for at least two to three days. After the occurrence of earthquake these waves return to normal frequency. By applying the technique a prediction can be made two to three days before the striking of any trembler.

Delineation of Levels of Risk and Seismic Risk Maps

According to Bolt (1999) predictions about the likelihood of earthquake occurrence in any given area are founded on seismic risk maps. These maps display the potential severity of future earthquakes in the mapped areas (Plate B, Figs. 1 and 2 and Plate C, Fig. 1). These are prepared on the base of historical records of past earthquakes and distribution of known faults in the particular area. Area of seismic gaps and earthquake periodicity could, also, be identified with the help of these maps (Press and Seiver, 2001, Plummer, *et al*., 2000 Bolt, 1999 and Sawkins, *et al.*, 1978).

The world seismicity maps showing relative earthquake risk zones were not available even in 1970's (Sawkins, *et al.*, 1978). For the first time it was recognized in 1970's that a great deal of money and effort should be directed towards earthquake prediction and possible control thereof (Sawkins, *et al.*, 1978. As a first time attempt the San Andreas Fault, which is an active fault system, was carefully monitored, regarding its shaking activity and for observable changes that might lead to a devastating earthquake (Sawkins, *et. al.*, 1978). However, in 1970's the possibility of accurately predicting earthquake of any magnitude was taken to be a remote goal.

The United States Geological Survey (USGS) published a map of United States of America showing the zones of relative probability of earthquake activity in early 1970's (Sawkins, *et al.*, 1978). The color-coded map of California (Plate A, Fig. 1) shown here is an example of the state-of-the-art maps used for probable earthquake forecasting. Areas shaded red have the highest probability.

As it is perceived generally that even a possible forecast of occurrence of an earthquake can reduce tremendous loss of life and property. The forecasts are generated from scientific data on factors, such as how the faults move and the average time between big temblors (Source: USGS Web Site). The world map of earthquake epicenters display only the sites of earthquake occurrence in the world, however, such maps help know the frequency of earthquakes in any area over the globe and the probability factor regarding the occurrence of any seismic activity here. The scientific developments have moved around and now the earth scientists are able to forecast an earthquake with more or less 100% expectation on the basis of recent seismic risk maps.

Frequency of Earthquakes

The data on the frequent strikes of earthquake in a particular area is vital to determine the frequency of earthquake occurrences in that area. The sources of the data include: paleoseismology, historical earthquakes and instrumental records. Quiescence in earthquake events is termed as seismic gap. The additional precursors to be studied for predicting an earthquake include: changes in elevation and tilting of surface, groundwater level fluctuations, changes in magnetic fields and electrical resistance, animals' anomalous behavior and increment in amplitude of ultra-low frequency radio waves (Bolt, 1999 and 1993).

Plate B

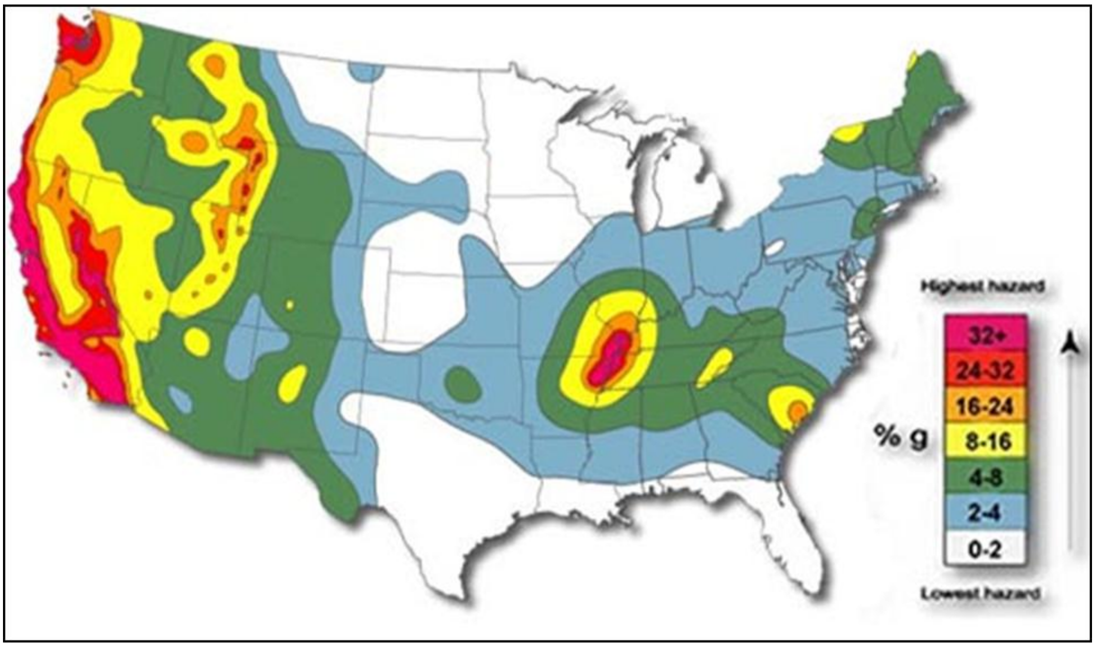

Fig. 1 Showing the Sisemic Hazard Map of USA (After Frankel, *et al.*, 2002 and 2000)

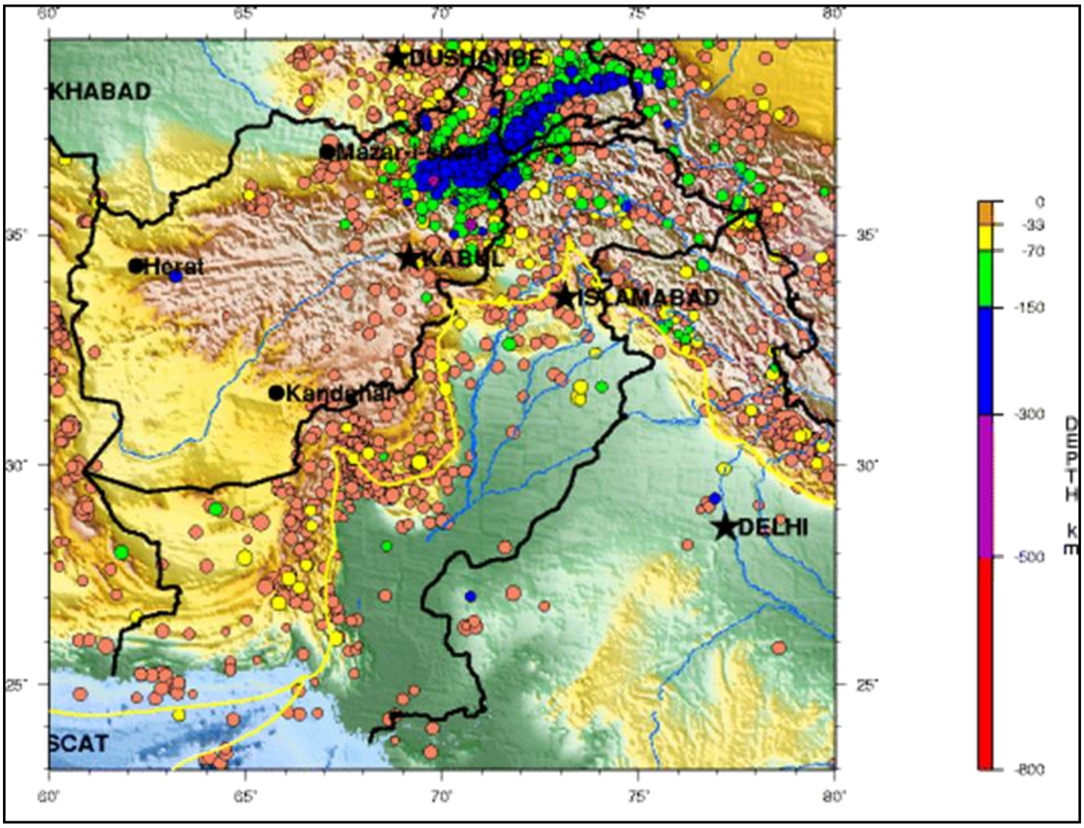

Fig. 2 Showing the Siesmicity Map of Pakistan from 1990 to 2000 (Source: Geological Survey of Pakistan, Quetta).

ASTAR and SRTM Satellite Images

Research work on earthquake prediction through artificial satellites is another modern tool in this regard (The Otoshmet Institute for Geophysics, Former USSR Report, 1976). According to this report by analyzing data received through the artificial space satellites an earthquake prediction before several hours could be made. This technique is based on that fact that prior to occurrence of any earthquake electromagnetic waves are released from the Earth surface, which are detected and recorded by sophisticated sensors of artificial satellites as signals. Seismologists today have a number of tools and techniques, like, SRTM and ASTAR images, at their fingertips to help predict earthquakes in any region around the world. The application of a modern satellite technology could advance towards a better earthquake predictive capability.

Crustal Deformation

The crustal deformation is studied to detect signs of pending earthquakes. While it is known that the Earth's crust deforms prior to a major earthquake. The prediction technique applying monitoring of crustal deformation is based on the fact that any changes, taking place in the Earth's surface/crust before a major earthquake, could be detected. Now-a-days it is an important aspect to be investigated by geo-scientists and seismologists with the use of satellites/satellites images and Global Positioning System (GPS) receivers. Several hundred GPS recorders have been installed at the site of Plate Boundary Observatory near Mt. Hood, Oregon (Plate C, Fig. 2), to monitor crustal strain throughout the western USA (Clement, *et al.*, 1999). These modern techniques are now successfully applied to precisely monitor the strain distribution in lieu of stress accumulation in active seismic zones.

GPS Total Station

The sophisticated GPS networks are being used to monitor the movements of Earth's crust and tectonic plates. Several GPS arrays have been deployed across tectonic plate boundaries to monitor very slow slip events. For example, an array of GPS equipment has been installed (Plate C, Fig. 2) across the Cascadia Subduction Zone, offshore Oregon and Washington State, USA (Clement, *et al.*, 1999). The information gathered by these devises is helping scientists create models of complex Earth deformation. The recent advances in GPS technology made it capable to record millimeter scale changes in the Earth's surface for detecting relative motion between the global tectonic plates. In the near past these motions were inferred from indirect evidence of the plates movements.

The investigations conducted by applying GPS technology show a remarkable result that the plates are moving nearly continuously along with episodic stick slip process. Analyses of the GPS data indicate that much of the slow pace movements between plates are taking place without producing earthquakes (McCaffrey, 1997). These movements have been dubbed the silent or slow-slip earthquake. Such disturbances originate 30 to 40km down, last between a day and a year, and can release the energy of a Mw 7.0 earthquake, but more very slowly and without ever being felt at the surface. Friction at these fault lines is greater than in the freely moving faults that allow tectonic plates to creep by each other smoothly, but less than that at patches where stress builds up and triggers a major quake. GPS is generally used to detect these silent quakes at the surface. For example, in Japan, the country with the biggest array of GPS devices, ten such events have been noted in the past decade (2001-10), disproving critics' claims that they are a rare and insignificant anomaly (Clement, *et al.*, 1999).

Acoustic Techniques

The acoustic techniques are based on sound waves and are applied for the prediction of seaquakes. This technique involves the placement of an acoustic sensor in the body of water for the detection of acoustic events. In this way characteristics of acoustic events are recorded. Signals are produced representing occurrence of tertiary waves. These signals are used to determine rate of occurrence of tertiary waves. The changes taking place in the rate of occurrence of tertiary waves are then analyzed. A decrease in rate of occurrence of tertiary waves is taken as a prediction of impending seismic activity on seafloor.

Paleoseismology and Historical Records

The data and records of paleoseismology and historical earthquakes have been proved as efficient tools to predict a seismic event. Several successful attempts have been reported in literature to make the most probable prediction of earthquake of some magnitude going to hit an area on the basis of these records (Bolt 1999 and 1993)

Seismic Array Technology and Earthquake Precursors

The worlds' first teleseismic recording seismometer was developed in 1889 (Ortiz and Bilham, 2003). While the newly developed seismic array technology is taken as a reliable tool for the identification of earthquake precursors in any

Plate C

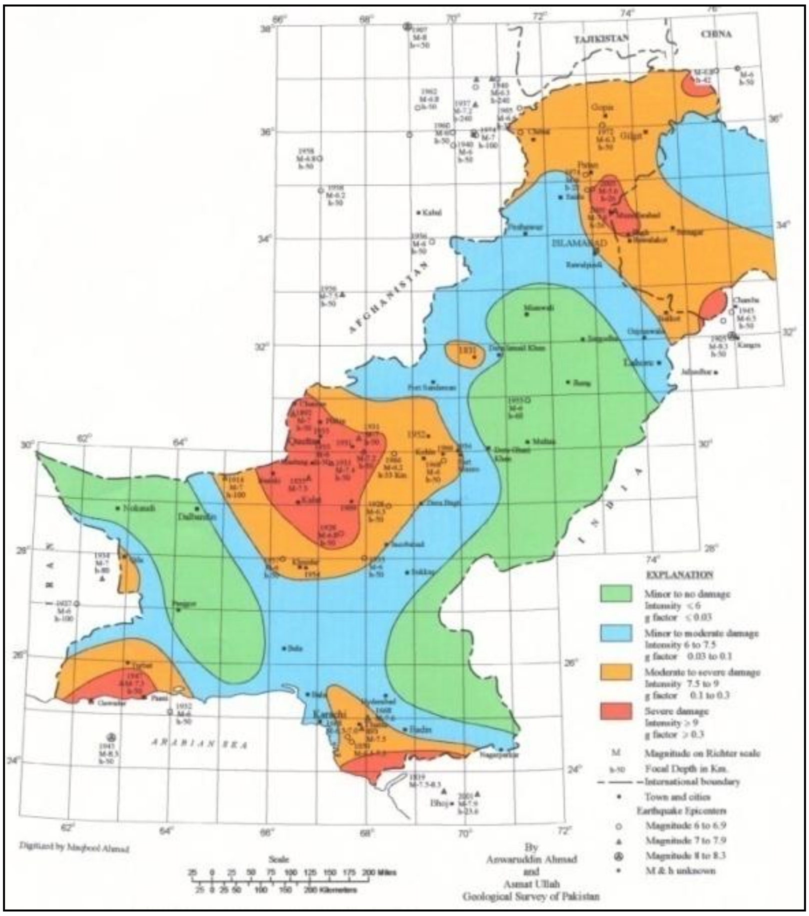

Fig. 1 Map showing the Seismic Hazard Zones of Pakistan (Source: Geological Survey of Pakistan, Quetta)

Fig. 2 Photograph showing GPS recorders installed at the Plate Boundary Observatory, Mt. Hood, Oregon, Western USA (Clement, *et al.*, 1999).

region by its vigilant seismic monitoring to foresee the point of time of an earthquake happening (Bolt 1999 and 1993). Out of a number of parameters, as discussed earlier in this paper, the seismic community has finally recognized the focal importance of earthquake precursors' identification for the reliable prediction of earthquakes. The community appreciated the importance of this experience in the light of perception that the elusiveness of earthquake precursors is a major cause in the failure to predict earthquakes.

InSAR Images

A modern technique, Interferometetric Satellite Aperture Radar (InSAR), monitors ground movements from space (Roach, 2004). It is known that earthquakes release energy suddenly caused by the sliding of a patch of the Earth's crust along a fault plane. However, the Earth also releases stress by creeping very slowly, causing no tremblers and damage to infrastructure. This slow creeping process and total strain budget may be monitored by InSAR images technique globally (http://news.nationalgeographic.com/). The World Agency of Planetary Monitoring and Earthquake Risk Reduction, Geneva, Switzerland terms it as a great modern technology. It illuminates the Earth surface and maps the incipient Earth deformation prior to an earthquake. The Global Earthquake Satellite System (GESS) employs this technology to detect minute deformations in the Earth's crust.

According to Roach (2004) the InSAR image technique involves examining pairs of the InSAR images of the same land surface area for the determination of changes and detection of slight deformations in the Earth's crust over very broad regions to millimeter-scale. In this way the satellites can detect and indicate built up strain prior to an earthquake. The technique is applied to monitor active fault zones over the globe. A constellation of InSAR-equipped satellite would furnish an extremely dense data set to be used for earthquake prediction.

DISASTER MITIGATION

The incidence and scope of earthquakes along with other natural disasters have placed disaster preparedness and management at the fore front of global and national development agendas since the 1990s (IUCN, 2006 and WHO, 2005). The destruction and devastation experienced during the fatal earthquakes of Kashmir, Oct. 8, 2005 and Ziarat-Gogai Earthquake Oct. 29, 2008, have reminded the need to chalk-out a comprehensive strategy for earthquakes mitigation. It has become now a direly required step to be taken at first priority for proper assessment of seismic hazards, proper planning for their mitigation, and designation of suitable designs for the construction of earthquake resistant (retrofitted) buildings by strictly applying the building code permission for different seismic risk zones.

CONCLUSIONS

The following conclusions have been drawn as an outcome of this review on the earthquake prediction techniques, particularly modern techniques in the context of natural disaster mitigation:

- The anomalous animal behavior, groundwater levels, seismic waves, acoustic techniques, crustal deformations, GPS total station, various satellite images, geo-electric signals and electromagnetic radiations had all been checked as possible indicators of earthquake occurrence.
- The present investigations reveal that no technique, till so far, could has been devised, which might facilitate a real time and precise forecast of an earthquake.
- No flawless method or instrument has been devised to date, capable to deliver hand information about this deathly devil of Earth so that the sudden loss of life and possession could be prevented.
- It is perceived, however that precise prediction of earthquake events is in sight in near future as the human perception and modern technology are advancing very fast.
- Seismologists and geo-scientists armed with a growing range of instruments and techniques are becoming more confident that their results are scientifically significant and useful. All over the world enthusiastic researchers are trying their hard to improve earthquake probability forecasts and are conducting research projects to achieve this direly needed goal of safe time prediction and hence prevention of loss of life and physical devastation.
- In spite of all that, off course, a solid connection to the three important variables: time, place and magnitude of an earthquake is still an elusive goal.

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