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Expanding Horizons in Mitigating Earthquake Related Disasters in Urban Areas: Global Development of Real-Time Seismology

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Abstract Real-time seismology is a newly developing alternative approach in seismology to mitigate earthquake hazard. It exploits up-to-date advances in seismic instrument technology, data acquisition, digital communications and computer systems for quickly transforming data into earthquake information in real-time to reduce earthquake losses and its impact on social and economic life in the earthquake prone densely populated urban and industrial areas. Real-time seismology systems are not only capable of giving rapid earthquake source information such as magnitude and epicenter but also spatial distribution of ground shaking in order to quick emergency response and rapid recovery efforts. Moreover, it provides early warnings before upcoming strong ground shaking in location of interests to reduce damage in critical infrastructure. In addition to faulting mechanism, it also provides finite-fault and rupture process information, such as slip distribution and rupture directivity, for large earthquakes in near-real-time to further assess extent of faulting and damage. The real-time seismology systems would play a key role to increase urban resilience and sustainability post disaster situations. Various advanced systems are currently operating in the earthquake prone countries such as Japan, United States, Taiwan, Mexico, and Turkey and in development stage in many others. The present study summarizes how the real-time seismology has globally developed to what extent it has been capable of earthquake hazard mitigation and why it is important for reducing earthquake disaster.

***Index Terms*— Real-time Seismology, Earthquake Early Warning Systems, Earthquake Hazard Mitigation, Disaster Mitigation, Shake Maps.**

I. INTRODUCTION

Real-time seismology has been recently developing approach in seismology to mitigate earthquake disaster. It exploits up-to-date advances in seismic instrument technology, data telemetry systems, digital communication systems and computer systems for quickly transforming data into earthquake information in real-time to reduce earthquake losses and its impact on social and economic life in the earthquake prone densely populated urban and industrial areas [1]. Real-time seismology systems are capable of giving rapid earthquake and tsunami information, comprising not only most common information of magnitude and epicentral location but also spatial distribution of ground shaking by means of ground acceleration, velocity and displacement in order to plan emergency response and recovery efforts in the earthquake prone areas. In some cases, it may even provide early warnings before upcoming ground motions to reduce earthquake damage to critical facilities such as power stations, high speed trains, subway etc. Furthermore, real-time seismology provides tsunami early warning against large offshore earthquakes. In addition to faulting mechanism, it also provides finite-fault and rupture process information, such as slip distribution and rupture directivity, for large earthquakes in near-real-time to assess extent of faulting and damage [2]. Further, recorded or estimated ground motions are converted into the intensity maps called "Shake Map" for practical and emergency recovery purposes [3]. New and more efficient algorithms have continuously been develop for reliable and faster earthquake early warnings and determinations of earthquake source parameters [4,5,6,7,8,9,10,11].

The recent catastrophic earthquakes in modern urban

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areas such as 1994 Northridge (California), 1995 Kobe (Japan) and 1999 Izmit (Turkey) earthquakes proved the need for rapid earthquake information systems. As urban resilience and sustainability have become a key factor in the future for densely populated urban areas [12], need for real-time seismology systems for large urban areas are becoming inevitable to overcome social and economic burden of a disaster caused by a destructive earthquake [13, 14].

The real-time seismology systems are functional in earthquake prone countries like Japan, USA, Taiwan, Mexico, Romania and Turkey with "ShakeMap" outputs. Further systems are in testing period in some countries and spreading quickly all over the globe (Fig. 1). The present study aims to give a concise review of global development of Real Time Seismology Systems and their importance in reducing earthquake disasters.

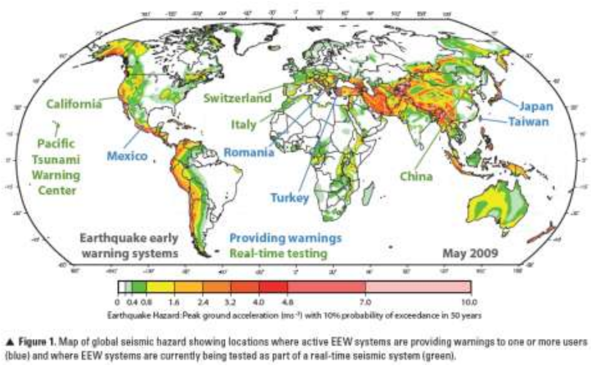

Figure 1. Global distribution of an earthquake hazard and Real-time Seismology System (obtained from [7]).

II. GLOBAL DEVELOPMENT

A. Japan

An early seismic alarm system comprising simple seismometers was employed by Japanese railway system in 1964 to automatically stop or slow down fast trains in case of a strong earthquake. A more recent and advanced system, Urgent Earthquake Detection and Alarm System (UrEDAS), which also gives a rapid estimation of earthquake magnitude and location, have been developed for railway operations. It was not until the devastating 1995 Kobe earthquake that a system covering whole Japan came up. Due to strong shaking of the Kobe earthquake both the seismic networks and communication systems failed and central government in Tokyo had no idea about the full extent of damage until many hours later [1]. Per the Japanese government action plan after the 1995 Kobe earthquake a very dense strong-motion seismic network, the Kyoshin Net (K-Net) consisting of 1000 stations was formed [4,15]. K-Net consists of 1,000 digital strong-motion seismometers with approximately 25-km spacing. Besides magnitude and epicenter location, the K-Net provides peak-acceleration contour map of a sizable earthquake with strong-motion center point (may be different from the epicenter of the earthquake) on this map. The K-Net data are released to its users through the Internet within several hours following the occurrence of an earthquake in Japan. Starting from K-net, Japan built one of the densest networks in the world such as Kiban Kyoshin Network (Kik-net) and High Sensivity Seismograph Netowrk (Hi-net). With these advancements, real-time seismology is applied as earthquake early warning systems and performance is recently tested with 2011 M_w9.0 Tohoku-oki earthquake [16,17]. Successfully thousands of people received early warning information in real time via cell-phones massages and media such as TV and radio.

B. Mexico

On September 19, 1985, an earthquake (M8.1) occurred in the Michoacan seismic gap of the Mexican subduction zone, 320 km west of the Mexico City. The earthquake caused many deaths and severely damaged many buildings in Mexico City [18, 19]. After the Michoacan earthquake a seismic early warning system called Sistema de Alerta Sismica (SAS) was developed. The aim of the SAS is to mitigate the effects of earthquakes generated in the Guerrero seismic gap of the subduction zone and to provide about 60 seconds of advance warning to the government officials and the residents of the Mexico City [18]. The SAS consists of a seismic detector system (12 strong-motion stations along the Guerrero coast), a digital telecommunication system (a VHF central radio relay station near the Guerrero coast and six UHF radio relay stations located between the Guerrero coast and Mexico City) and a central control system located in Mexico City from which the signal that triggers the automated public alert receivers is broadcast. 58 AM and FM radio stations, 6 open TV channels, 25 public schools, government agencies with emergency response functions, the national electric power utility and main public transportation system (the Metro) are equipped with special SAS receivers that disseminate the alert signal from SAS. Audio alerting mechanisms are also used for warning dissemination. The SAS has been a pioneering system in the world for the dissemination of public early seismic alert signals since 1993 with several successful early warnings [20].

On September 14, 1995, a magnitude 7.2 earthquake occurred in the Guerrero seismic gap. Upon the occurrence of the earthquake the SAS was activated and a signal was received in the Mexico City 72 seconds before the arrival of ground motion [19]. In 18 radio stations, the statement "Alerta Sismica" is automatically broadcast while in the remainder of radio stations the statement is broadcast with the intervention of human operator. SAS receivers in public schools were triggered and evacuations took place according to the drills held at schools. Besides, warning towers broadcast a clearly audible signal, providing the residents adequate time to evacuate their apartments according to the previous trainings. Occurrence of the damaging 15 June 1999 Oaxaca earthquake (M 6.7), prompted the Department of Civil Protection of Oaxaca state to construct the Sistema de Alerta Sísmica de Oaxaca (SASO) in 2003 [18]. The SASO system has issued three public alerts for important earthquake events as well as five preventive alerts for moderate ones. The governmental authorities of Oaxaca and Mexico City have agreed to integrate the functions of SASO and SAS in a single entity of Seismic Alert System of Mexico (SASMEX) for better efficiency

C. Taiwan

Central Weather Bureau (CWB) of Taiwan completed a dense seismic instrumentation program in 1996, with mostly strong-motion seismographs [21]. This program also includes a rapid earthquake information release system based on 61 real-time telemetered digital acceleographs. Upon occurrence of an earthquake, this system automatically determines the location and magnitude of the earthquake, prepares a shake map and disseminates the information to the governmental emergency response agencies electronically in four ways, by pager, e-mail, WorldWideWeb and fax. During the September 21, 1999, Chi-Chi earthquake, Taiwan Rapid Earthquake Information Release System (RTD) performed successfully [21]. Within 102 seconds after the earthquake's origin time, RTD automatically disseminated the hypocentral parameters, the magnitude and shake map to its users. Within 5 minutes after the origin time, about 30 fire department chiefs and 10 CWB staff received the pager message. Within 102 seconds of the origin time an output report posted on the Web. Within about 2 minutes, the output report was faxed to 246 designated fax users including government departments, rescue agencies and public media. Within 2 minutes of the origin time, RTD sent out an e-mail report of the earthquake, which also include a preliminary shake map, to its e-mail users. The e-mail users include some seismologists in Taiwan and overseas and staff members of the four nuclear power plants, several dams, Taiwan Electric Power Company and the natural disaster prevention center of the National Science Council. The network has also provided an extensive data set that was distributed rapidly to seismologists around the World for earthquake researches [22]. A Real-time Online earthquake Simulation system (ROS) has been developed to simulate regional earthquakes in Taiwan, based on the real-time earthquake source parameters provided by the RTD [22]. The ROS outputs are ShakeMap and ShakeMovie for a given earthquake. It takes about 3 minutes for an earthquake to calculate the outputs following 2 minutes required for the inputs provided by the RTD. On top of these systems, very recently Taiwan initiated an EEWS with high-density seismic network based on low cost sensors, called Palert. This algorithm focuses on on-site algorithm rather than usual network based EEWS [23].

D. United States

In 1990, California Institute of Technology (Caltech) and US Geological Survey Pasadena office initiated the Caltech/USGS Broadcast of Earthquakes (CUBE) project for rapid information release after an earthquake in southern California [1]. CUBE automatically reports earthquakes recorded by 350-station seismograph network. Within a few minutes of a sizable earthquake, designated scientists, fire and emergency departments, and subscribers to the system-such as railroad companies, utility companies and TV stations are notified about the earthquake's location, size and depth via pager. In 1993, University of California at Berkeley and USGS Menlo Park office initiated a similar rapid broadcasting system in northern California, namely REDI (Rapid Earthquake Data Integration) [24]. In 1997, Caltech, USGS and California Division of Mine and Geology (CDMG) initiated a joint research and development project, TriNet, in order to build a state-of-the-art real-time earthquake information system in southern California [1,3]. TriNet has capability of generation of shake maps, which portray the extent of potentially damaging shaking within the 3-5 minutes after an earthquake in southern California [3, 25]. Shake map includes observed ground motion as well as intensity values obtained from the ground motion values [26]. Shake maps can be used for emergency response, loss estimation and public information. The shake maps are organized in a database and made available on the WorldWideWeb (http://www.trinet.org/shake). Following October 16, 1999, Hector Mine, south California, earthquake CUBE system broadcast first estimation of location and magnitude of the earthquake to its users in about 3.5 minutes via e-mail, WorldWideWeb and pager [27]. TriNet system produced first shake map within 4 minutes of the event [25, 26].

Since 2006 the USGS has been trying to develop EEW for the USA, by cooperating several organizations including the California Geological Survey (CGS), the California Institute of Technology (Caltech), the California Office of Emergency Services (CalOES), the Moore Foundation, the Southern California Earthquake Center (SCEC), the Swiss Federal Institute of Technology, Zürich, the University of California, Berkeley, and the University of Washington. The aim is to build and run an EEW system for areas at risk beginning with the West Coast states: California, Washington, and Oregon [28].

A demonstration EEW system, ShakeAlert, started sending test notifications to selected users in California starting from January 2012. The system find out earthquakes using the California Integrated Seismic Network (CISN), an existing network of about 600 high-quality ground motion sensors. CISN is built by cooperation between the USGS, State of California, Caltech, and University of California, Berkeley, and is one of seven regional networks that make up the Advanced National Seismic System (ANSS).

ShakeAlert is shifting from the demonstration system to a production prototype for the West Coast of USA. In following five years, system is expected to complete and begin issuing public alerts.

E. Turkey

A major earthquake hit the north western provinces of Turkey on August 17, 1999 and devastated Turkey's industrial heartland, causing ten thousands of fatalities and billion dollars of economic loss. The city of İstanbul, with a population of over 10 million people, was also hit severely. The earthquake's strong ground shaking and fault rupture smashed Turkey's lifeline. Electric power transmission lines were damaged, leaving earthquake struck area without electricity. Telephone and cellular phone communications were paralyzed and communications with the earthquake struck area became impossible. The highway crossing the area was also damaged. The full extent of the damage and what areas sustained the most serious damage were not known to the government officials in Ankara, capital city of Turkey, many hours later. Even government executives were able to communicate with the area with the help of the live broadcasting facilities of a private TV channel. As a result, decisions regarding search and rescue, medical emergency response and other critical response needs had to be made while the earthquake information was still incomplete.

The earthquake clearly demonstrated that the need for a rapid earthquake information release system for Istanbul and its environs was vital. Because, Istanbul and its environs have a dense population, house the main industrial facilities of Turkey and had been effected by many large earthquakes prior to the 1999 Izmit earthquake [29, 30]. If there had been a real-time seismic network in the region, it would have generated a shake map and the government and public executives would have been able to know areas likely to have suffered damage within the several minutes following the 1999 Izmit earthquake. Such a system may have even provided early warning about 26 seconds before upcoming strong-ground motion at Avcılar, a district of Istanbul took the blunt of the damage [31,32]. Though the warning time may have been much shorter for other sites in the earthquake struck area, a 5-10 seconds of early warning for a possible future earthquake can provide an opportunity for automatic trigger measures, such as the shutdown of high energy, gas distribution, manufacturing facilities, stoppage of the subway cars and the elevators, the opening of fire-exits and critical infrastructure such as bridges etc [33,34,35].

As Istanbul has been facing biggest earthquake risk in Turkey following the 1999 Izmit earthquake [29,30] a dense real-time strong motion network, known as İstanbul rapid response and an early warning system (IERREWS), was established in 2002 [36,37]. The system is aimed to provide rapid post-earthquake maps including Shake, Damage, and Casualty maps), data for strong-ground motion and structure response and early-warnings for emergency purposes such as slowing down of high-speed and underground trains and shut down of pipelines and manufacturing operations to minimize fire hazards and prevent further damage. Currently, Kandilli Observatory and Earthquake Research Institute (KOERI) operates three EEWS: Virtual Seismologist, PRESTo and ElarmS-2 [38,39].

Early Warning Systems in Turkish Legislation, Public Institutions Plans and Reports

• In the item 13/B of the *Law No.5902* on the Organization and Duties of Disaster and Emergency Management Presidency, has been mentioned the necessity of establishment of early warning systems.
• In the *"Strategy Plan 2013-2017"* of Turkish Prime Ministry Disaster & Emergency Management Authority (AFAD), early warning systems are discussed under specific headings.
• In Objective No: 11 of *"Integrated Urban Development Strategy and Action Plan 2010-2023"* (KENTGES), Mitigation of Disaster and Settlement Risks is one of the main topics.
• In the Report of National Council of Earthquake *"National Strategy for Reducing Earthquake Losses - May 2002*" it's discussed that comprehensive, medium and long-term earthquake mitigation efforts must be done before earthquake.
• In 1061th item of the 10th Development Plan 2014-2018, it's mentioned that mitigation, preparedness, response and post-disaster rehabilitation works should be carried out in integrity.
• Under the main title named *"Strategy A.1.4" in "National Earthquake Strategy and Action Plan - UDSEP"*, national earthquake preliminary damage estimate and the development of early warning systems are discussed in detail.
• In 2.1th part named "Integration Stages" of *"National Disaster Intervention Plan of Turkey – TAMP"* "Establishing, developing and testing early warning systems" have mentioned as a rule.

III. DISCUSSION AND CONCLUSIONS

To minimize the immediate impact of large earthquakes in the earthquake prone modern urban areas, one of the effective approaches called the real-time seismology has been developed with the use of most advanced seismic receivers, data acquisition and telemetry systems in seismology [1,40,41]. Real-time seismology systems provide a rapid estimation of the earthquake parameters (origin time, epicentral location and magnitude) and the ground motion distribution or shake maps to its users to effectively organize recovery efforts and emergency response, to minimize social disruption and to help urban resilience/sustainability after large earthquakes.

Although, various EEWS are in operation, they are not perfect and systems sometimes ended up failure. Among many issues, there are three main important parts that needs to be improved: I) optimum station distribution of a seismic network should be identified [42] II) inaccurate magnitude estimation should be avoided [43] III) new approaches are needed to decrease false alarm [44] such as false alarms due to explosions in quarry blasts [45,46,47].

Real-time seismology systems are currently operating in the earthquake prone countries such as Japan, United States, Taiwan, Mexico and Turkey and in a development stage in some others. These systems performed successfully after the 1995 Guerrero earthquake in Mexico, the 1994 Northridge, 1999 Hector-Mine, and 2014 South Napa earthquakes in United States, the 1999 Chi-Chi earthquake in Taiwan and 2011 Tohoku-oki earthquake in Japan [48]. The 1999 Izmit earthquake in Turkey clearly demonstrated that the need for real-time seismology systems are essential for earthquake prone, densely populated and industrial areas of Turkey for effective planning of emergency response and making of critical decisions immediately after an earthquake. It is suggested that these systems are a necessity in earthquake prone urban areas of the globe for better earthquake resilience.

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