UNIVERSITI PUTRA MALAYSIA

DETECTION OF PRECURSORY SIGNALS OF PAST EARTHQUAKES USING INTEGRATION OF SPATIO-TEMPORAL PARAMETERS

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By

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Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in fulfilment of the Requirement for the Degree of Doctor of Philosophy

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August 2013

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The preparation process of an impending earthquake may leave fingerprints on the earth's surface. Earthquakes are triggered when the energy accumulated in rocks releases causing ruptures in the ground or movements in place of the existing faults. Elastic strain in rocks, formation of micro-cracks, gas releases and other chemical or physical activities in the earth's crust before and during earthquakes has been reported to cause rises in temperature, surface latent heat flux (SLHF), upwelling index and chlorophyll-a (Chl-a) concentration on the ground or sea surface. This study examines variations of the mentioned factors before several past oceanic, coastal earthquakes occurred at the Pacific and Indian Oceans together with two pairs of successive inland earthquakes in Kerman and Azerbaijan provinces, Iran. The sudden partial releases of the elastic energy which has resulted to the main events are believed to be detected by seismographs and remote sensing techniques. Pre-earthquake anomalies prior to all case study earthquakes were detected. Our detailed analyses on oceanic/coastal earthquakes

revealed 1–5°C rises in surface temperature in epicenter areas. Considerable anomalies in Chl-a concentration, five weeks to a day before the earthquake events which are accompanied by the raises in upwelling indices were detected. Time series of SLHF also showed meaningful rises from one month to one week before the main events. The anomalous patterns started developing several weeks before earthquakes and disappeared after the main shocks. Significant rises in SLHF may lead us to understand the energy exchange mechanism during earthquakes and at the period of aftershocks, as well.

The most interesting factor which yielded considerable results for almost all earthquake instances was SLHF. In case of offshore and coastal earthquakes the Chl-*a* was found to be the most common precursor. Most of the anomalous patterns were in accordance with local and regional active faults which have been already proposed as triggering structures by international research organizations. The seismographic records were also successfully used for confirmation of the earth's movements during the preparation stage of the main event of Ahar as an underlying cause for remotely sensible phenomena.

The author strongly believes that with proper use of remote sensing data, expert analysis of seismographs from nearby stations (which unfortunately are not existing everywhere), advanced in-situ measurement devices, and thorough information about local and regional active faults developing local earthquake prediction systems for earthquake prone region would not be impossible.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGESANAN ISYARAT AWAL GEMPA BUMI YANG LEPAS MENGGUNAKAN INTEGRASI PARAMETERS RUAWG-MASA

Oleh

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Ogos 2013

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Proses penyediaan gempa bumi yang bakal berlaku boleh meninggalkan kesan pada permukaan bumi. Gempa bumi yang dicetuskan apabila tenaga yang terkumpul di dalam batu membebaskan menyebabkan pecah dalam tanah atau pergerakan di tempat kesalahan yang sedia ada. Terikan anjal dalam batu, pembentukan mikro-retak, siaran gas dan aktiviti kimia atau fizikal yang lain dalam kerak bumi sebelum dan semasa gempa bumi telah dilaporkan menyebabkan kenaikan suhu, permukaan terpendam fluks haba (SLHF), upwelling indeks dan kepekatan klorofil-a di atas tanah atau permukaan laut (Chl-a). Kajian ini mengkaji variasi faktor-faktor yang disebutkan sebelum ini beberapa lautan yang lalu, gempa bumi berlaku di pantai Pasifik dan Lautan India bersama-sama dengan dua pasang gempa bumi pedalaman berturut-turut di Kerman dan wilayah Azerbaijan, Iran. Pengeluaran secara tiba-tiba sebahagian daripada tenaga anjal yang telah mengakibatkan kepada peristiwa-peristiwa utama yang dipercayai dikesan oleh seismograf dan teknik penderiaan jauh. Anomali pra-gempa bumi sebelum gempa

bumi semua kajian kes telah dikesan. Analisis terperinci mengenai lautan/gempa bumi pantai mendedahkan 1-5° C kenaikan suhu permukaan di kawasan pusat. Anomali besar dalam Chl-a, lima minggu ke sehari sebelum kejadian gempa bumi serta kenaikan indeks upwelling telah dikesan. Siri masa SLHF juga menunjukkan peningkatan yang bermakna dari satu bulan satu minggu sebelum peristiwa-peristiwa utama. Corak anomali mula kilihatan beberapa minggu sebelum gempa bumi dan hilang selepas kejutan utama. Peningkatan yang ketara dalam SLHF boleh membawa kita untuk memahami mekanisme pertukaran tenaga semasa gempa bumi dan pada tempoh gempa susulan.

Yang paling menarik faktor yang memberikan keputusan yang besar untuk hampir semua kejadian gempa bumi adalah SLHF. Dalam kes gempa bumi luar pesisir dan pantai Chl-a didapati yang paling biasa. Kebanyakan corak ganjil adalah selaras dengan kesalahan aktif tempatan dan serantau yang telah pun dicadangkan sebagai mencetuskan struktur oleh organisasi penyelidikan antarabangsa. Rekod seismograph juga berjaya digunakan untuk pengesahan pergerakan bumi pada peringkat penyediaan satu acara utama Ahar sebagai penyebab untuk fenomena jauh waras. Penulis percaya bahawa dengan penggunaan yang betul data remote sensing, analisis pakar seismograf dari stesen berdekatan (yang malangnya tidak ada di mana-mana), maju dalam-situ alat pengukuran, dan maklumat yang menyeluruh tentang kesilapan aktif tempatan dan serantau membangunkan sistem ramalan gempa bumi tempatan bagi kawasan gempa bumi cenderung tidak akan menjadi mustahil.

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I am grateful to all data providers and the NASA teams. We thank to the scientists of International Research Institute of Climate and Society (IRI/LDEO) and Asia Pacific Data Research Center (APDRC). We also acknowledge the MODIS mission scientists and associated NASA personnel for the production of the data used in this research effort. We thank to the IRIS data management center. The seismic instruments were provided by the Incorporated Research Institutions for Seismology (IRIS) through the PASSCAL Instrument Center at New Mexico Tech. Upwelling indices for the Pacific Ocean have been downloaded from Pacific Fisheries Environmental Laboratory (PFEL). AMSR-E data is provided by the National Space Development Agency of Japan (NASDA).

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APPROVAL

I certify that a Thesis Examination Committee has met on 30th August, 2013 to conduct the final examination of Habibeh Valizadeh Alvan on her thesis entitled "Detection of precursory signals of past earthquakes using integration of spatio-temporal parameters" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the University Putra Malaysia [P.U. (A) 106] 15 March 1998. The committee recommends that the student be awarded Doctor of Philosophy.

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This thesis was submitted to the senate of University Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

HABIBEH VALIZADEH ALVAN

Date: **30 August 2013**

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CHAPTER 1

INTRODUCTION

1.1 Scientific background

Sudden movements of the earth's crust are the ultimate production of gradual tectonic deformations on regional or continental scales. During the quiet period that the mechanical forces are built up in the crust, underground materials reshape, break, and move to allow higher capacity of the elastic crust to absorb the pressures. When the accumulated energy exceeds the ground's resistance, the surface ruptures, or moves in the place of existing faults, allowing the energy released in the forms of seismic waves and other forms of energy like heat during foreshocks, main shake, and aftershocks. A chain of underground events which are triggered by these waves and heat before and during this stage may produce physical/chemical interactions prior to the main shake. During the past decades there have been several researches about the appearance of the atmospheric, oceanic and surface changes during this preparation stage prior to strong and moderate earthquakes. Recent advances in remote sensing sensors and techniques have allowed more accurate monitoring of the earth's surface and producing more comprehensive reports in terms of coverage, variety, and time.

Currently, there are several theories about the types and the sequence of events during the geological stages of earthquakes. Most explanations stress on raises in heat and the

generation of seismic waves as the main signs of an impending earthquake. Their differences only lie in the secondary phenomena which are triggered by these events. Anomalies in surface (sea, land, and air) temperature, heat flux, upwelling index, chlorophyll-a concentration, radon (or other underground) gas releases, and ground deformations are considered as the precursors of earthquakes. Among all these theoretical factors which may or may not happen during an earthquake, possible variations in the amount of surface latent heat flux (SLHF), sea & land surface temperature (SST & LST), and surface chlorophyll-a (Chl-a) are easier to record from the earth observing satellites. SLHF is the amount of energy exchange in the form of water vapor between the earth's surface and atmosphere. Abnormal variations in this factor have been repeatedly reported as an earthquake precursor. The accumulated stress in the earth's crust during the preparation phase of earthquakes is said to be the main cause of temperature anomalies weeks to days before a main event and subsequent shakes. Chemical and physical interactions in the presence of underground water lead to higher water evaporation prior to inland earthquakes. In case of the oceanic earthquakes, higher temperature at the ocean beds may lead to higher amount of Chl-a on the sea surface. On the other hand, it has been also said that the leak of Radon gas which occurs as rocks break during earthquake preparation causes the formation of airborne ions and higher air temperature (AT).

1.2 Problem statement

Occurring with no early warning, sudden slip on a fault causes destruction and large scale loss of lives. Much of the devastation results from falling structures. However, the secondary deadly events like fires, gas leak, accidents, etc. may also take place during a moderate or strong earthquake. Earthquakes are expected to occur in parts of the world with previous records of shakes. A possible short-term earthquake prediction system implemented in an earthquake-prone region allows performing in-time actions prior to an impending earthquake.

Such a warning system can be based on the detection of several abnormalities produced during the preparation stage of earthquakes. Like any other system, first, the basic requirements, opportunities, and deficiencies should be assessed. There is a need for theories and theoretical explanations and analyses for judging the relevancy of the proposed assumptions to different cases. Accuracy assessment and uncertainty calculation are the next phases of any possible forewarning method. Apparently, for a better understanding of the operation mechanism of this geo-related hazard, it should be characterized in terms of earthquake faults involved in past events, geological setting (like identifying unconsolidated sediment and unstable land), and tectonic movements. Unfortunately, there is a general lack of geo-related information in most parts of the world. The hidden and surface faults are not accurately mapped and amplifying or transferring attributes of different regions of the crust have not been determined for many earthquake-prone areas. Nevertheless, the emergence of remotely recorded data

and processing techniques allowed different national and international information providers and data vendors to produce various levels of image, map, and statistical data. However, on the other hand, in-situ measurements which are necessary for recording some underground or surface events are very hard, costly, and time consuming.

As a part of the initial efforts for using remote-sensing-based information for earthquake prediction, this thesis is about detecting remotely sensible variations which are possibly related to past earthquakes and might had been used for predicting the event. Inland, coastal and oceanic earthquake instances from different parts of the world are studied and relevant data processing techniques are applied for separating possible seismo-related abnormalities from seasonal and non-related ones. Previous efforts were often limited to one or two factors and concentrated on the small areas around earthquake epicenters lacking the role of impacting geological structures (fault zones) and recorded ground movements which would be expected to occur before main quakes. By taking into consideration the natural trend of surface and near surface factors, geological structures, and available geo-scientific theories, the relevancy of the studied factors of monitoring pre-earthquake signs are evaluated.

This sort of research helps identifying those datasets (remote sensing, seismography, maps, and historical records), processing techniques, and analyses which can be used in determining the directions of possible future prediction systems. Earthquake types, depths, origins, and epicentral areas are different in various parts of the world. So, although there might be a chance for identifying some general precursory events which

are globally common, a prediction system would be local and very specific to a number of factors that appear and sensible in a particular earthquake-prone region. In order to overcome the general lack of geo-related knowledge which is hard and expensive to acquire, the latest, advanced remote sensing should be used. However, sometimes, atmospheric effects, geological characteristics, and earthquake attributes make it too hard to detect a possible precursor prior to an earthquake. Before going into the determination of the necessities of a local prediction system in micro scale, the factors, techniques, and data appropriate for macro study of the area should be identified. This large-scale examination of the situation in case of a past major shake allows the recognition of important geological structures like active faults, seismic and aseismic plates, and geo-mechanical regime of the case study area which determines the transferring characteristics of seismic waves from an origin (which might be a fault zone, etc.) to an epicenter.

1.3 Research objectives

The general objective of this thesis is to identify the remotely-sensible events which may be related to the seismic activities resulted in past earthquakes. The usefulness of previously suggested precursors, appropriateness of available theories on the physical and chemical events during the seismic activities, and applicability of analysis and visualization types for different inland, coastal, and oceanic earthquakes are inspected.

The specific objectives of this study include:

- To identify meaningful, remotely sensible variations in land, sea and air temperature (LST, SST, AT), surface latent heat flux (SLHF), and chlorophyll-a (Chl-a) anomalies on earth's surface prior to past earthquakes.

- To discover the variations of the above-mentioned factors which are in relation with seismic activity in epicentral regions and local fault systems prior to past earthquake events.

- To characterize the co-occurrence and sequence of the possible precursory events specific to each case study earthquake.

1.4 Research questions

To fulfill the research objectives, several research questions were postulated:

- Which on and above surface phenomena have already been recognized as earthquake precursors, and which data is needed to assess them?

- What are the best datasets to map the earth's surface during earthquakes? How are they qualified and verified?

- What is the fitness for use of this data? How can this fitness for use be measured, in order to assess the overall uncertainty of earthquake forecasts?

- Is it possible to identify the source and propagation patterns of seismic waves triggering an earthquake? And basically is it needed to gain complete knowledge about the local fault regime and tectonic settings?

- Is it possible to develop regional prediction models based on the past earthquakes experienced in the area? What seasons are ideal for earthquake prediction and how strong an earthquake should be to be remotely sensible?

1.5 Structure of thesis

This thesis consists of a descriptive research about the variations of the above-mentioned remotely sensible factors recorded during past seismic activities in different parts of the world. Statistical data on the reoccurrence intervals of previous shakes are used together with the map locations of the area's faults to determine the coarse geographical extents and time periods of monitoring operations. Seismographic data are also used for mapping weak signs of foreshocks and aftershocks which often are not reported by international earthquake bodies. Analyses on the concurrences of several precursory events are also done. In order to minimize the non-related events, the case study earthquakes are chosen from different parts of the world with different seasonal, altitude, and latitude conditions. Basically this sort of research could be the cornerstones

of a possible future short-term earthquake prediction system. The thesis is made up of seven chapters, each corresponding to the objectives and contributing towards an advance understanding of the remotely sensed earthquake precursors. This first chapter introduces the thematic context of the study, the main research problem, the motivation to pursue the research, and the research objectives, questions and goals.

The second chapter reviews literature related to the proposed topic. Previous efforts on approaches and techniques about changes on remotely sensible factors and seismograph reports prior, during and after earthquakes are reviewed which reveals needs for further development in known or unknown earthquake precursors.

The third chapter explains an improved framework for earthquake precursory factors detection. Description of remote sensing and seismological data of most used and freely available resolutions to public acquired from different sources are presented. As well as the concept of remote sensing techniques and seismography in earthquake precursors monitoring, the details and criteria of analyses and interpretations, and the cons & pros of each procedure are discussed.

Chapter four is a collection of descriptive analyses done on the remotely sensed variations for past coastal and oceanic earthquakes all over the world. Critical analyses were done in terms of the epicenter locations and fault locations for discovering seismic activity and evaluating the earthquake mechanisms declared by research and monitoring institutes.

In the fifth chapter of this thesis, the past inland earthquakes are studied for the concurrency of remotely sensed factors while one of the main concerns is to assess the capability of remote sensing methods in specifying the location and extents of the active faults involved in the preparation activity. Analytic description of distribution of small foreshocks through the processing of continuous seismograms from nearby stations was also used to evaluate the detected changes and movements of the ground.

Finally, chapter six focuses on the summary, conclusions, contribution, and recommendations for future research, bringing the book to a close.

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