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Earthquake Precursors (Indicators): A Review on the Earthquake Forecasting/Prediction Studies from Past to Present

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Abstract

The earthquake forecasting/prediction is a very difficult scientific and socio-economic problem, and it is examined from the decision theoretical standpoint. However, the earthquake precursors/indicators have been preferred to make an estimation of the future events on a statistical base. Extensive researches have failed to find reliable precursors although there are some occurrences such as foreshock, aftershock, swarms, seismic quiescence, seismic activation, etc. Studies on earthquake precursors have been performed for over 150 years and many parameters such as radon concentration, electric and electromagnetic signals, spatio-temporal analysis of earthquake distributions, stress variations, precursory seismic rate changes, ionospheric total electron content variations have been used to make successful earthquake estimations. However, the successful estimations of the next events depend on the location-time-magnitude knowledge. Thus, the principle problem in forecasting/prediction studies is whether the precursors can be used to forecast/predict the future earthquake. Although there have been many approaches for the estimation of earthquakes, these applications can be divided into two parts: the first class is based on the empirical observations of precursory ground motions, whereas the second one is based on the statistical models of seismicity. Although these models have several advantages or disadvantages compared to each other, the best approach does not exist. In the light of studies from past to present, earthquake forecasting/prediction should be accessible, well documented and should specify: (i) time window, (ii) spatial window, (iii) magnitude window, (iv) author's confidence level in the prediction and (v) chances of the earthquake's happening anyway, as a random event. Thus, earthquake precursors should be well documented and should specify region-time-magnitude window as well as the evaluating and monitoring of the well-known geophysical and other precursors. However, some questions will live with us for a long time: (i) why is earthquake prediction research not progressing faster? (ii) what comes next in the dynamics of lithosphere and earthquake prediction? (iii) do the precursors exist? (iv) finally, is prediction possible?

1.Introduction

Earthquakes generally occur without any warning and therefore they are the most feared natural hazards. The Earth's crust has a complex structure and earthquakes are accepted as chaotic phenomenon. Therefore, the seismic precursors (indicators) can be used to predict the future earthquakes on a statistical basis [1]. Basic types of statistical earthquake precursors consist of many occurrences such as foreshock, aftershock, swarms, seismic quiescence, seismic activation, etc. Also, many parameters such as dilatancy (an increase in volume) of rock, the radon concentration, groundwater level and temperature, changes in the animal behaviors, electric and electromagnetic signals, precursory fault slip, chemical emission, temporal variation of seismic wave velocities, spatio-temporal distribution of earthquakes, precursory seismicity rate changes, stress distribution, ionospheric total electron content variations can be monitored as precursory changes in order to make successful earthquake prediction [2]. In addition, many well-accepted seismological, geodetic and other geophysical precursors such as geomagnetic, geo-electric, geodetic and gravity precursors, ground fluid or hydro-seismology can be evaluated and monitored for a reliable earthquake prediction. However, the success of these forecasting/prediction studies depends on the knowledge of location-time-magnitude of the next earthquake [3]. Hence, the main problem in the earthquake forecasting/prediction studies is whether or not the statistical properties of earthquake occurrences can be used to forecast/predict the next earthquake.

Earthquake prediction can be made in three scientific hypotheses: (i) the phrase of *"short term prediction"* states the alarms from days to months, (ii) *"intermediate term prediction"* from a few months to several years, and (iii) *"long term prediction*" to from a few years to several decades. It is clear that examples of forecasting/predictions include the intermediate or long terms evaluations of the future earthquakes. However, examples of successful short-term predictions for the next earthquakes have been uncommon. However, in the terminology, earthquake forecast and prediction are classified into long-term (decades), medium (intermediate)-term (years), short-term (months to weeks) and imminent (weeks to days, even hours) ones, and the phrase 'forecast and prediction' is used in the sense that 'forecast' is expressed in probability, or the increase of probability of earthquakes, whereas 'prediction' is in most cases by alarms [4]. In this sense, the understanding of the concept regarding to 'forecast' and 'prediction' has no significant difference from the international seismological community.

3. Observations and Monitoring the Potential Earthquake Precursors/Indicators

Earthquake prediction researches have been conducted for over 150 years with no obvious successes. Many researchers aimed at the prediction of imminent future earthquakes. But, extensive searches have failed to find reliable precursors. Because, theoretical works suggest that faulting is non-linear process which is highly sensitive to unmeasurably fine details of the state of the Earth in a large volume, not just in the immediate vicinity of the hypocenter [3]. Forecast/prediction, especially since 1950s, has been one of the main issues in the earthquake science in many parts of the World. Hence, large scale of field investigation of earthquake science was achieved, especial in the USA and China.

Monitoring of potential earthquake precursors can be achieved through different disciplines: seismological, geodetic, geo-electric and geomagnetic, and ground fluid or earthquake hydrology/hydro-seismology. These observation networks are both for scientific purposes and for the monitoring of potential anomalies. Thus, infrastructures for seismological, geodetic, and the other geophysical observation and monitoring have been developed and modernized considerably by a series of national regional projects. In the light of all notes given in the literature, earthquake prediction should be accessible, well documented and should specify: (i) time window, (ii) spatial window, (iii) magnitude window, (iv) author's confidence level in the prediction and (v) chances of the earthquake's happening anyway, as a random event [5].

4. Results and Discussions

According to the literature studies including laboratory experiments and real observations, the direct attribute to earthquake prediction is the precursors. Researchers focused on the searching precursors from seismic sequences and geodetic observation data, and explored the relationship between the earthquake occurrence and anomalies in observation data of gravity, geomagnetism, geo-electricity, groundwater, as well as some other parameters as briefly discussed below.

3.1. Seismic Precursors

The well accepted seismic precursors are increased moment release and seismic quiescence before earthquake occurrences. There are many precursors related to the precursory seismic patterns commonly used in the earthquake prediction practice. They can be classed as increased moment release (more small earthquakes than usual), seismic quiescence (fewer small earthquakes than usual, a significant decrease of the main seismicity rate as compared to background rate) in intermediate-term to short-term of next earthquake epicentral area, foreshocks, aftershocks, earthquake migration (related to geodynamic condition and tectonic settings in a specific time window/range), seismic gap, seismic stripe (defined as the small to moderate earthquakes clustered in linear pattern) within specific tectonic area in short term [3].

3.2. Seismicity Parameters

The relation between earthquake parameters and the changes of seismicity parameters as well as structure parameters and 'target' earthquakes, that is, region-time-magnitude of the 'target' earthquakes based on the seismicity parameters can be basically obtained from empirical studies of previous earthquake cases. In addition, pattern recognition, data mining and other modern computational tools can be used [6]. Also, analysis of seismicity parameters such as b-value of the Gutenberg-Richter magnitude-frequency relationship, focal mechanism parameters, stress state parameters, Vp/Vs ratio, Qc of the coda wave can play the key roles in the routine works of earthquake forecast and prediction.

3.3. Geomagnetic and Geo-Electric Precursors

Ground–based electro-magnetic observation related to earthquakes may be developed. This type of evaluation can be divided into geomagnetic and geo-electric field observations and electromagnetic perturbation observation. It is stated that this type of observation can be include in apparent resistivity observation beneath the earth [2]. The electric field strength is the only parameter used as the precursor related to forthcoming earthquake activities in the surrounding region. These studies show that electromagnetic signals are distributed heterogeneously in space-time. In spatial distribution, the abnormal signals before the earthquake were recorded in some stations [7].

3.4. Electromagnetic Emission Precursors

A number of recent studies provides examples from several parts of the World by which relations between possible electromagnetic precursors and earthquakes become more and more plausible although electromagnetic information is not recorded before each earthquake. It is stated that DC-ULF (direct current-ultra low frequency) electromagnetic signals show a precursory time from few days to several weeks. This method also became more popular after the occurrence of Tangshan, China, earthquake. Also, some obvious electromagnetic abnormity is recorded at three stations before May 12, 2008 Venchuan (Ms=8.0) earthquake. On May 9th, 3 days before main shock, the amplitude of high frequency information increased sharply at the same time in two components at Gaobeidian station [8].

3.5. Seismic Electric Signals

Selectivity is one of the most important properties of seismic electric signals (SES) which are related to earthquakes. Molchanovet al. (1998) [10] analyzed the precursory effects in the subionospheric VLF (very low frequency) signals for the Kobe earthquake. They discovered a statistically significant change of terminator time characteristics, which began a few days before the main shock and probably continued a few weeks after it as a transient oscillation with period about 10 days. Thus, it is suggested that subionospheric VLF propagation can be considered as a rather promising candidate for a short-term earthquake precursor.

3.6. Apparent Resistivity Precursors

An effective parameter in seismic activity changes is given the conductivity of the media below the earth and it shows the apparent resistivity in daily use [2]. A study by Zhang et al. (2009) [10] indicates some possible apparent resistivity abnormity related with the Wenhchuan (Ms8.0) earthquake. Their results show that before the Wenhchuan earthquake, apparent resistivity amplitude at one observing direction decreased about 7.2% at Pixian station, 30 km away from the earthquake epicenter with duration time more than 2 years, and turned to rise 5 months before mainshock.

3.7. Geodetic and Gravity Precursors

Monitoring the ground deformation for the earthquake prediction by using geodetic and gravity observation began in 1960 and after 1966 Xingtai strong earthquake, this type of observation stations gradually expanded to all mainland [2]. Geodetic precursors come from the observation methods of tilt by horizontal water pipe tilt meter or vertical pendulum tilt meter at stable stations, short/long leveling and base line of stable and/or portable stations, bore hole volumetric strain and/or directional component strain, stable/portable GNSS, and field observation cross active faults or portable networks. The most commonly used gravity precursors is gravity field. The anomalous increasing-decreasing conjunction areas of relative gravity changes indicate the future potential areas of earthquake. Thus, relative gravity changes are related to crustal mass movement and the landform.

3.8. Ground Fluid or Hydro-seismology and/or Earthquake Hydrology

Earthquake indicators from ground fluid are generally two types: physical precursors and chemical precursors [2]. Physical precursors are water level, temperature and conductivity. Chemical precursors are chemical components and gases of groundwater and soil of fault zone, which is provided to play a significant role in short term earthquake prediction. Statistical studies show that the lasting time and spatial distribution range of these indicators are contributed to the magnitude and location of future event, which means time has clues for next earthquake magnitude assessment and region indicator. An example of precursory anomalies of ground fluids were observed as associated with the recent Ludian Ms=6.5 earthquake on August 3rd, 2014.

3.9. Groundwater Level, Temperature and Geochemistry

In ground fluid monitoring network, well water level measurement is the most common approach to observe physical anomalies [2]. In the early time of earthquake prediction after 1966 Xingtai earthquake, the water level change was measured by workers with ruler or analog technique and recorded in hand-made figures, or continuous analog machine recordings, the data sampling frequency was once per hour (highest), or once a day (generally) at 8:00 am each day. Thus, sharply changes in water level (increasing or decreasing) is considered as short term indicator of earthquake occurrence. Regarding to the water temperature of wells with confined aquifer system, in some cases, the changes from temperature keep pace with water level, and some cases do not [2]. Geochemistry precursor generally comes from content measurement of chemical components of groundwater, i.e., ion, trace elements, gas and/or radioactive gases, etc. The measured value of mentioned items higher or lower than two times of mean value is considered as anomaly. After testing a few stations, some ion and gas contents was measured in several active tectonic regions and proved to be effective in short to imminent term before recent occurred Ludian Ms=6.5 earthquake [2].

3.10. Other Precursors (in testing or in debate)

Apart from the precursors mentioned above, some predictions testable or in debate can be given.

A brief review of possible seismic precursors suggests that tilt, hygroreception (humidity), electric, and magnetic sensory systems in animals could be linked into a seismic escape behavioral system. Several testable predictions of these analyses have been discussed, and it is recommended that additional magnetic, electrical, tilt, and hygro-sensors be incorporated into dense monitoring networks in seismically active regions [11].

Recently, a relationship between ionospheric TEC (total electron content) anomalies and different earthquake magnitude groups before the main shocks was investigated by Ulukavak et al., (2020) [12]. These analyses clearly show that the day-to-day changes in TEC anomalies may supply significant precursors prior to the global earthquakes ($M \geq 6$) in the short-term earthquake prediction for main shocks. However, the efficiency of data analysis of ionosperic TEC analysis to the short term earthquake prediction is still in test.

Recent years have seen an ever increasing interest in studying the usefulness of radon measurements in earth sciences. Hence, the abnormal radon exhalation from the interior of earth, as a precursory phenomenon related to earthquakes and as an indicator of underlying geological faults, is an important field of investigation. Riggo and Santulin (2015) [13] suggested in their study that the results seem to indicate that the radon is a good indicator of crustal activity such as earthquakes, but there are still many tests to be done to achieve a deterministic forecast. Nevertheless, the prediction of catastrophic earthquake is a scientific objective. Thus, radon studies regarding earthquake prediction in soil gas have been made many parts of the World.

Kirschvink (2000) [11] stated that at least four possible candidates for animal sensitivity can be gleaned: (1) ground tilting, (2) humidity changes, (3) electrical currents, and (4) magnetic field variations. Apparent tilt precursors prior to strong earthquakes have been reported in Japan and China. However, the magnitude of these precursors appear to be in the range of a few *micro*-radians, acting over several hours before the earthquake. The process of humidity reception in animals is known as hygroreception. The recognition that changes in groundwater level might sometimes provide clues to an impending earthquake suggests that associated changes in local humidity might be detected by animals. The presence of electrical and optical precursors prior to earthquakes is an area of intense research. Although successful predictions have been made in different parts of the world, the seismic community is understandably skeptical [11].

Ultra-low frequency (ULF) magnetic field variations are perhaps the least understood class of possible earthquake precursors. Most of these studies arose from luck—magnetic observatories just happened to be recording some features of the geomagnetic field for other reasons when the earthquake occurred, and as such they often experienced power failures and data gaps as a result. General consideration in these studies is that meaningful data can only be obtained when recording instruments with adequate sensitivity and bandwidth just happen to be present very close to the epicentral area [14-15].

In summary, earthquake prediction studies have been conducted for over 150 years without clear successes. However, extensive researches have failed to observe reliable precursors. Although some researchers assert that 'earthquakes cannot be predicted', history of some authors is rife with fits of optimism and disappointment. It is well known that earthquakes do not occur randomly in space and time. Thus, many researchers have made many studies on earthquake prediction by developing different approaches and discussed possible precursors mentioned above.

5. Conclusions

This paper makes summarizes the earthquake forecasting/prediction studies in the literature. Although there are many claims of 'successful predictions' and a few correct predictions have been made, a large number of studies have failed to find systematic and reliable indicators. Also, seismology is such a young science that the cause off earthquakes was discovered in the 1950s only. In this context, the systems for earthquake prediction must include systematic monitoring activities, the quality control system and consultation system for the assessment of time-dependent seismic hazard or earthquake prediction. The approaches must combine different observations and detailed analyses for time-depended seismic hazard at different spatio-temporal scales have characteristic properties which are a combination of statistical, empirical and physical considerations.

Thus, it seems that many questions will continue to be discussed for a long time: (i) Why is earthquake prediction research not progressing faster? (ii) What comes next in the dynamics of lithosphere and earthquake prediction? (iii) Do the precursors exist really? (iv) Do we have strategies for the precursor evaluation? (v) What needs to be done to get earthquake prediction research into a productive mode? (vi) Do we have suitable/correct algorithms for the next generation of earthquake prediction? (vii) Finally, is prediction possible?

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. He has no known competing financial interests or personal relationship that could have appeared to influence this paper.

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