The Time-Predictable Model of Earthquake Prediction: A Standard Tool for Hazard Prediction?

Mrs. Savi V. Shende
M.Sc. (Environmental Science), NET
Lecturer, M. Patel Institute of Engineering & Technology, Gondia (M.S.) – 441 614
savivijayshende@rediffmail.com

Devendra Pandey
Assistant Professor, M. Patel Institute of Engineering & Technology, Gondia – 441 614
devpand_2000@yahoo.com

Dr. Shailendra Singh Rathore
Principal, M. Patel Institute of Engineering & Technology, Gondia – 441 614
www.ssrathore.com

Abstract: As with so many natural phenomena, earthquakes are the product of what scientists call "complex systems," or systems which are more than the sum of their parts. Not just speaking proverbially, but in truest ever sense, precise prediction of earthquakes has long been a question of *Life & Death* for the scared inhabitants of earthquake-prone areas and so is for the forecasters and scientists ranging from Nostradamus to Dr. Vladimir Kellis-Borok since last a few centuries. Though the experts still don't know many of the details of the physical processes involved and how to predict these events, several prediction and chaos theories have been put forth with varying degrees of successes. In spite of the inherent complexities involved in such a complex system, the research is still on and on.

The time-predictable model of earthquake prediction is based on the theory that earthquakes in fault zones are caused by the constant build-up and release of strain in the Earth's crust. This model has become a standard tool for hazard prediction in many earthquake-prone regions and, therefore, it is not surprising that the scientists in the United States and other Pacific Rim countries, such as Japan and New Zealand, routinely use this technique for long-range hazard assessments when adequate data are available.

(1) Introduction: Exactly What is Earthquake Prediction?

When humans wondered in early centuries why the Earth sometimes trembles, and yearned to predict these frightening disturbances for thousands of years, Ancient cultural explanations of earthquakes were often along the lines of the mythical Japanese Namazu: A giant catfish with the islands of Japan on his back. A demigod, or daimyojin, holds a heavy stone over his head to keep him from moving. Once in a while the daimyojin is distracted so Namazu moves and the Earth trembles.

Earthquakes are more deadly than any other form of weather hazard[1]. They have killed 2.7 million people during the period of 1900 to 1976[2]. In comparison 1.8 million people were killed by all natural disasters combined together, excluding earthquakes. Numerous forecasts and scientists earthquake predictions, ranging from Nostradamus[3] to Dr. Vladimir Kellis-Borok[4,5,6,7], have been made since last a few centuries. Several prediction and chaos theories of earthquake predictions have been put forth with varying degrees of successes over the years including but not restricted to seismicity patterns, crustal movements, elastic rebound[8], ground water level in wells[1,2,9], earthquake clouds[10], changes in ion concentration in the ionosphere[11], various types of electromagnetic indicators including infrared and radio waves, radon and hydrogen emissions[12,13], telluric currents[14,15], and even unusual animal behavior[1,2,16]. The mystery of earthquake occurrence frequently sparks people without scientific training into claiming that they have found the solution to the earthquake prediction problem. Discredited, fantastic theories of predicting earthquakes include weather conditions and unusual clouds, and the phases of the moon.– These pseudoscientific theories and predictions ignore the requirement of rigorously formulating the hypothesis and to test it statistically.

Self-appointed prediction experts often resort to the technique of making vague statements, which they claim were correct predictions, after an earthquake has happened somewhere. Rudolf Falb's "lunisolar flood theory[17]" is a typical example from the late 19th century. And, therefore, it is necessary to define what exactly an earthquake prediction is.

According to the Seismological Society of America, for a statement to be accepted as a valid earthquake prediction, it has to contain the expected magnitude with error limits, the well defined area of the epicenter, the range of dates, and the probability of this to come true. The data from which the prediction was derived must be verifiable and the analysis of these data must be reproducible. Long term predictions (years to decades) are more likely to be achieved than medium term predictions (months to years), and short term predictions (hours to days) are in general unlikely to be possible, at present.

If a plausible mechanism linking the observations with the predicted earthquake is not offered, the credibility of the prediction is diminished, but it may not necessarily be rejected. Evaluations of apparent successes must include a statistical estimate of the probability that the prediction came true by chance, which is often the case with predictions by amateurs. Whether a prediction is scientific or amateurish is not based on who makes the prediction, but based on how the prediction is made and tested. Predictions can be formulated either by defining the limits of the parameters probabilistically or by firm values within the rigorous bounds.

(2) The Theory of Elastic Rebound

The theory builds on the older concepts of continental drift[18], developed during the first decades of the 20th century (one of the most famous advocates was Alfred Wegener), and was accepted by the majority of the geoscientific community when the concepts of seafloor spreading were developed in the late 1950s and early 1960s. Probabilistic estimates of earthquake hazard use various models for the temporal distribution of earthquakes, including the 'time-predictable' recurrence model formulated by the Japanese geophysicists K. Shimazaki and T. Nakata in 1980[19], which incorporates the concept of elastic rebound described as early as 1910 by H. F. Reid[8].

Following the great 1906 San Francisco earthquake, Harry Fielding Reid examined the displacement of the ground surface around the San Andreas Fault[8]. From his observations he concluded that the earthquake must have been the result of the elastic rebound of previously stored elastic strain energy in the rocks on either side of the fault. The elastic rebound theory is an explanation for how energy is spread during earthquakes. As plates on opposite sides of a fault are subjected to force and shift, they accumulate energy and slowly deform until their internal strength is exceeded. At that time, a sudden movement occurs along the fault, releasing the accumulated energy, and the rocks snap back to their original undeformed shape. In geology, the elastic rebound theory was the first theory to satisfactorily explain earthquakes. Previously it was thought that ruptures of the surface were the result of strong ground shaking rather than the converse suggested by this theory.

In an interseismic period, the Earth's plates move relative to each other except at most plate boundaries where they are locked. The far field plate motions cause the rocks in the region of the locked fault to accrue elastic deformation. The deformation builds at the rate of a few centimeters per year, over a time period of many years. When the accumulated strain is great enough to overcome the strength of the rocks, an earthquake occurs. During the earthquake, the portions of the rock around the fault that were locked 'spirng-back' to original position, relieving the displacement in a few seconds that the plates moved over the entire interseismic period. The time of strain accumulation could be months to hundreds of years, while the time of ‘spring-back’ action is in seconds. Like an elastic band, the more the rocks are strained the more elastic energy is stored and the greater potential for an event. The stored energy is released during the rupture partly as heat, partly in damaging the rock, and partly as elastic waves. Modern measurements using GPS largely support Reid’s theory as the basis of seismic movement, though actual events are often more complicated.

(3) The Time-Predictable Model of Earthquake Prediction

The Time-Predictable Model of Earthquake Prediction states that an earthquake occurs when the fault recovers the stress relieved in the most recent earthquake. In other words, earthquakes in fault zones are caused by the constant build-up and release of strain in the Earth's crust. Unlike time-independent models (for example, Poisson probability), the time-predictable model is thought to encompass some of the physics behind the earthquake cycle, in that earthquake probability increases with time. This model has become a standard tool for hazard prediction in many earthquake-prone regions and, therefore, it is not surprising that the scientists in the United States and other Pacific Rim countries, such as Japan and New Zealand, routinely use this technique for long-range hazard assessments when adequate data are available. For example, the U.S. Geological Survey (USGS) relied on the time-predictable model and two other models in its widely publicized 1999 report projecting a 70-percent probability of a large quake striking the San Francisco Bay Area by 2030.

According to this model, when an earthquake occurs on the fault, a certain amount of accumulated strain is released. Following the quake, strain builds up again because of the continuous grinding of the tectonic plates. If the size of the most recent earthquake and the rate of strain accumulation afterward is known, one should be able to forecast the time that the next event will happen simply by dividing the strain released by the strain-accumulation rate. Arising from the Elastic Rebound Theory, geophysical precursors preceding an earthquake may be divided into five stages, each stage manifesting a typical set of changes in the earth as follows[1, 20, 21, 22, 23, 24]:

Stage I: As the two sides of a fault move, elastic strain slowly builds up in the rocks, and the rock particles become compressed together.

Stage II: It is the stage of dilatancy and development of cracks. The rocks are now packed as tightly as possible, and the only way the rocks can change shape is to expand and occupy a larger volume. This increase in volume is called dilatancy. The volume increase is caused by the formation of microcracks. As microcracks form, the water that normally fills the pores and cracks in the rocks is forced out, very much like stepping on wet beach sand. Air now fills the pores and cracks in the rocks. During this process, the rocks become stronger and can store more elastic strain. This process can be detected on the surface by uplift and tilting of the ground.

Stage III: During this stage, water is forced back into the pores and cracks in the rocks by the surrounding water pressures, much like when water fills the footprint in the sand. As the water returns, the dilatant rock loses its increased strength. The rocks are already strained beyond their normal capacity, and the rate at which the rocks fall in strength determines the instant of failure. The inflow of water also prevents further generation of microcracks; thus, the rocks stop expanding. In addition, the water in the rocks provides lubrication for the eventual release of the built-up strain.

Stage IV: Eventually, the rocks can no longer resist the strain; the fault suddenly ruptures, releasing the elastic energy stored in the rocks in the form of heat and seismic waves. It is these waves that constitute an earthquake.

Stage V: It is the manifested by the sudden drop in stress followed by aftershocks. Most of the elastic strain energy is released by the principal earthquake; however, additional smaller ruptures occur producing aftershocks. The aftershocks release the remaining strain energy, and eventually the strain in the region decreases and stable conditions return.

(4) Study Casts Doubt on Validity of Standard Earthquake-Prediction Model

“Whether accumulation of strains is necessarily a precursor to an earthquake is still unclear,” says Trudy Bell[15]. Although the time-predictable model makes perfect sense on paper, following studies have raised serious questions about this fundamental technique for making long-range earthquake predictions:

STUDY I: James C. Savage[25], a USGS geophysicist at Menlo Park, is measuring strain accumulation in the San Andreas fault by terrestrial laser ranging. His group made measurements two weeks, one week, and one day before a magnitude 6.2 earthquake near Morgan Hill, California, on 24th April, 1984. Just by happenstance, they made their measurements close to the earthquake’s epicenter. But within the accuracy of the measurements, they saw no change in the rate of the strain accumulation before the quake. Although this results was discouraging, “may be the earthquake was not large enough to see any anomaly,” concluded Savage.

STUDY II: When Stanford University geophysicists decided to put this model to the test using long-term data collected from an ideal setting, their obvious choice was Parkfield - a tiny town in Central California midway between San Francisco and Los Angeles. Perched along the San Andreas Fault, Parkfield became a heaven for geophysicists for the simple reason that it has been rocked by a magnitude 6 earthquake every 22 years on average since 1857. The last one struck in 1966, and geologists have been collecting earthquake data there ever since. Parkfield is a best place to test the model because we have measurements of surface ground motion during the 1966 earthquake and of the strain that's been accumulating ever since. It's also located in a fairly simple part of the San Andreas system because it's on the main strand of the fault and doesn't have other parallel faults running nearby.

When Murray and Segall[26] applied the time-predictable model to the Parkfield data, they came up with a forecast with 95 percent confidence that a magnitude 6 earthquake should have struck the San Andreas Fault in Central California have taken place between 1973 and 1987 - but it didn't. In fact, 15 years have gone by. As the results were consulted with the Stanford

Statistics Department just to make sure that this was done as carefully and precisely as anybody can, the researchers are quite confident that there's no way to fudge out of this by saying there are uncertainties in the data or in the method.

Can these observations be disregarded as an exceptional case? Could the time-predictable method work in other parts of the fault, including the densely populated metropolitan areas of Northern and Southern California? The researchers have their doubts. At Parkfield, things are fairly simple, while at Bay Area or Los Angeles, there are a lot more fault interactions there, so it's probably even less likely to work in those places. The model's poor performance in a relatively simple tectonic setting does not bode well for its successful application to the many areas of the world characterized by complex fault interactions.

(5) Summary & Conclusions

Despite being a few negative observations, the basic concept behind this method is so scientific that its applicability can not altogether be rejected. But the things are not as simple as they look. Speaking metaphorically, there may be lot many undercurrents crossing & crisscrossing each other in a complex pattern beneath the calm surface of an ocean. It just might be simple to measure the stress getting accumulated in a single fault, but how to account for the stresses being attributed by the parallel (or oblique) faults running nearby? Till all doubts are resolved, ‘Use with Caution’ is the message to all geophysicists about this model.

Recent Japan earthquake, 2011, and the subsequent gruesome-Chernobyl-nightmare in Fukuyama nuclear plant has undisputedly shown that the financial, infrastructural, nuclear, and climate crises are individually serious issues after a major earthquake, but in combination their impact could be catastrophic for the environment and global economy too. Authors fervently hope that the technological advances in earthquake science would make long-range forecasting a reality one day. Earthquakes are now a globally recognized as significant global threat and, as a consequence, debate over the need to understand our mother earth more has moved upto the top of the agenda amongst geologists, geophysicists, and government. Precise geodetic measurements are now possible with latest generation strains-meters and GPS. Agencies and geophysicists involved in all such studies and investigations has the responsibility for issuing meaningful forecasts with whatever information they have at their disposal, so that city planners and builders can use the best available knowledge for the benevolence of the environment and society as a whole.

(6) References

(1) **A Review of Two Methods of Predicting Earthquakes**, Chris Gray, University of Wisconsin, Madison, http://tc.engr.wisc.edu/uer/uer96/author3/index.html.

(2) **Earthquakes, Animals and Man,** B. G. Deshpande, Pune, India: The Maharashtra Association for the Cultivation of Science, 1987.

(3) **The Prophecy of Nostradamus About the Recent Japan Earthquake (*Century: 1, Quatrain: 46*),** *Very near Auch, Lectoure and Mirandea great fire will fall from the sky for three nights. The cause will appear both stupefying and marvelous; shortly afterwards there will be an earthquake.*

(4) **Variations of Trends of Indicators Describing Complex Systems: Change of Scaling Precursory to Extreme Events**, Vladimir Keilis-Borok (University of California, Los Angeles) and Alexandre Soloviev (International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences) appears in the (J.) *CHAOS.*

(5) **Geometric Incompatibility in a Fault System,** Andrei Gabrielov, Vladimir Kellis-Borok, & David D. Jackson, Earthquake Prediction: The Scientific Challenge (National Academy of Sciences Colloquium, United States), 1996, pp. 3838-3842.

(6) **Nonlinear Dynamics of Lithosphere and Earthquake Prediction**, Volume 2002, Dr. Vladimir Kellis Borok & Dr. Alexandra A. Soloviev, ISSN 0172-7389, ISBN 3-540-43528-X, Springer-Verlag Berlin Heideberg New York.

(7) **Intermediate Term Prediction of Occurrence Times of Strong Earthquakes**, Keilis-Borok, V.I., Knopoff, L., Rotwain, I. & Allen, C.R. (1988). *Nature* 335 (6192): 690–694.

(8) **The Mechanics of the Earthquake, The California Earthquake of April 18, 1906**, H.F. Reid, Report of the State Investigation Commission, Vol. 2, Carnegie Institution of Washington, Washington, D.C. 1910.

(9) **Water Level and Strain Changes Preceding and Following the August 4, 1985 Kettleman Hills, California, Earthquake**, Roeloffs, E. et al. (1997), *Pure and Applied Geophysics* **149**: 21–60.

(10) **Earthquake Clouds**, D.J. Li, Xue Lin Public Store, Shanghai, China, 1982, pp. 148-150.

(11) **Da rumort es ständig im Untergrund,** De Swaaf, Kirt, Interview with Pier Francesco Biagi". Der Standard, 22nd March 22, 2011.

(12) **Precursory Chemical Changes in Ground Water: Kobe Earthquake, Japan**, U. Tsunogai & H. Wakita, Science 269 (5220): pp. 61–63, 1995.

(13) **Earthquake Chemistry II, Collected Papers**, Edition II., H. Wakita, Laboratory for Earthquake Chemistry, Faculty of Science, University of Tokyo, 1996.

(14) **Modelling the Impact of Telluric Currents on Earthquake Activity, G. Duma,** Geophysical Research Abstracts, Vol. 8, 01730, 2006, SRef-ID: 1607-7962/gra/EGU06-A-01730, © European Geosciences Union 2006.

(15) **Earthquake Prediction: Keeping an Ear to the Ground**, Trudy E. Bell, Spectrum IEEE, May, 1988, Vol. 25, Issue 5, INSPEC Accession Number: 3190809, pp. 47-52.

(16) **When the Snakes Awake: Animals and Earthquake Prediction,** Helmut Tributsch, Cambridge, Massachusetts: The Massachusetts Institute of Technology, 1982.

(17) **The Falb Earthquake Theory**, The New York Times, June 26, 1887.

(18) **Die Herausbildung der Grossformen der Erdrinde (Kontinente und Ozeane), auf geophysikalischer Grundlage**, Alfred Wegener, *Petermanns Geographische Mitteilungen* 63: 185–195, 253–256, 305–309, 6th January 1912.

(19) **Time-Predictable Recurrence Model for Large Earthquakes**, Shimazaki, K., and T. Nakata, 1980, , *Geophys. Res. Lett.*, *7*, 279-282.

(20) **Earthquake Prediction**, Tsuneji Rikitake, The Elsevier Scientific Publishing Company, Amsterdam, Netherlands, 1976.

(21) **California Quake**, Larry L. Meyer, Sherbourne Press, Nashville, 1977.

(22) **Earthquakes**, Bruce A. Bolt, W. H. Freeman and Company, New York, 1988.

(23) **Earthquakes and Geological Discovery**, Bruce A. Bolt, New York: Scientific American Library, New York, 1993.

(24) **Earthquakes**, G. A. Eiby, Van Nostrand Reinhold Company, New York, 1980.

(25) **Strain Accumulation in Western United States**, James C. Savage, Annual Review of Earth and Planetary Science, Vol. 11, 1983, pp. 11-43.

(26) **Testing Time-Predictable Earthquake Recurrence by Direct Measurement of Strain Accumulation and Release**, Jessica Murray & Paul Segall (2002). Nature 419, pp 287-291, 19th September, 2002.

* * *