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GUEST EDITORIAL

The grand challenge of earthquake prediction

The grand unifying theory in Earth sciences, called plate tectonics, provides the theoretical underpinnings of earthquake generation. This theory tells us that the Earth's top solid crust is divided into various tectonic plates, and they are all in relative motion as they move at less than a snail's pace over the underlying semi-molten material. While some of them grind past each other or go under, there are areas where they are colliding to form huge mountains – like the Himalayas. The borders of these opposing plates are locales where tremendous strain accumulates over long periods, and, finally, the stresses overwhelm the strength of the rocks, generating quakes that result in releasing the stored energy outward through seismic waves. Thousands of small earthquakes occur every day – the question is why some of them evolve as massive earthquakes.

Every time a major earthquake occurs, the scientific community often encounters a question: why can't they predict earthquakes as they do for the weather. The advent of technology makes it possible to monitor all weather-related processes, even though some of their complex interactions evade numerical modelling and precise predictions. For the earthquakes, the causative processes are further complex and are beyond the realm of direct observations. As of today, there are no models that can predict the time, places, and sizes of future earthquakes. Unlike the atmospheric processes, neither their causative factors nor their interactions are measurable. All earthquakes nucleate at depths of tens of kilometres below the surface of the Earth, and we do not have enough understanding of the properties of rocks, including the pressure, temperature and attendant complexities, including the role of fluids at those depths to resolve that question. Ultimately, the success of earthquake prediction science depends on the ability to quantify these processes and their interactions.

Issuance of short-term earthquake warnings, anywhere from minutes to months before an earthquake, can be made only in the event of detecting an observable precursory signal. Therefore, short-term earthquake prediction remains a grand challenge. Early earthquake warning systems are active in some parts of Japan, the western US and Mexico. It works on recording the lag in the time of arrival of a faster-moving *P*-wave and *S*-waves emanating from an earthquake that originates 200–300 km away from the recording station. Thus, a warning of 25 sec to 35 sec can be issued to the target cities before the arrival of the damaging *S*-wave to gain time to shut down any critical facilities. Although insufficient for evacuating people from high-rises, such a system may be a doable proposition for a city like Delhi, located about 250 km from the Himalayas – a known source of great earthquakes.

We have made progress in finding the probability of an earthquake occurring in a region for decades and how much stress is building up in a particular region. In some places, we also know how often big earthquakes occur, estimated based on the overall budget of accumulated versus used-up slip in earlier earthquakes. We can call this a 'long-term forecast', and scientists have been able to make such forecasts of earthquake vulnerability in some parts of the world, like the Himalayan arc, which would help improve earthquake preparedness and thus mitigate damages. One practical way to deal with that kind of knowledge is to generate scenarios of site-specific ground motion in response to expected maximum near-field quake magnitudes. Most deaths in earthquakes are caused by failure of infrastructure due to ground shaking. And, for forecasting damage, it is important to know how severe it is shaking in a given location, which is generally most severe near the epicentre – the point on the surface directly above the earthquake source but perceivable even 100 kilometres away.

In order to assess the long-term earthquake hazard, we need to acquire two important pieces of information. One, how often do earthquakes occur in a given source and two, how severely the ground shakes in a particular area. For the former piece of information, scientists use historical data, and if it is of a limited nature, it is possible to use the geological data on active faults to extend the database beyond the written records. Thus, probabilistic seismic hazard maps of different regions are made based on estimating the ground shaking.

Such 'long-term forecasts' rely on statistical models based on the earthquake history of the place and close monitoring of the current seismicity. Knowing the recurrence period or pattern of earthquakes on specific fault lines will also help in long-term forecasting. Scientists have been able to make such long-term forecasts in some parts of the world, such as California. Satellite-based radar imaging of surface deformation prior to an earthquake is a new tool that aids in earthquake forecasting. The combined use of satellite-based measurements and modelling of crustal deformation and fault-specific geological studies have made such forecasts possible, at least in some regions, like the high probability of a major earthquake in the central Himalayas. In summary, the current state of knowledge helps to identify the most likely region of an earthquake disaster. However, obtaining an estimate of the precise timing, location and size of the likely event is beyond the present capabilities.

To understand this issue further, we must go back to the first and only successful case of an earthquake prediction – the 4 February 1975 Haicheng earthquake in north China. The story unfolded during the murky days of China's Cultural Revolution, and the exact details came out much later after a team of seismologists visited the affected areas and consulted the people involved in this exercise to bring out the facts. They concluded that what happened in the 1975 Haicheng earthquake was a case of a successful prediction with some caveats. The leader of the fact-finding team, Kelin Wang, describes this as 'a blend of confusion, empirical analysis, intuitive judgment and good luck'. The precursory signals included land level changes in the nearby areas that prompted an initial long-term earthquake warning. But a short-term warning was later given based on the increased foreshock activity. The location of the quake was also identified. Taking the cue from the warnings, locals began leaving the area, and when the 7.3 magnitude earthquake eventually occurred at 7:36 p.m., it killed about 1,000 people. The euphoria of this apparent successful prediction, however, was short-lived. On 28 July the next year, a 7.6 earthquake in Tangshan could not be predicted as there were no precursory foreshocks or land level changes, and 250,000 people lost their lives. As we know, short-term prediction could not be repeated elsewhere because it is difficult to differentiate the regular occurrence of smaller earthquakes and what could be termed a precursory sequence at the time of their occurrence – an insight most often gained in hindsight.

Some scientists think that during the preparatory stages of earthquakes, micro-cracking occurs in the source regions and generates electromagnetic emissions in various frequencies. So, the idea is to catch this signal before the earthquake strikes a particular area. Another interesting prospect lies in the fact that large earthquakes trigger earthquakes on neighbouring faults because the elastic energy that is released impacts other faults nearby. Understanding the state of stress in a region may help to devise models of earthquake forecasting. In the publication, 'Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space', issued by the National Academies of Sciences, Engineering, and Medicine (2018), it is explained that progress in earthquake forecasting can be made by continuously observing areas prone to earthquakes using space-based InSAR and high-resolution optical imagery. For massive earthquakes, temporal variations in gravity may reveal large-scale deformation not observable by other methods. It is encouraging that the long-term GPS measurements of surface deformation in some subduction zones like the Cascadia, where a great earthquake is expected, reveal that steady strain accumulation is punctuated by creep events at the down-dip limit of the locked fault. The M 9.0 Tohoku earthquake and many other recent large events, including the 2004 Sumatra–Andaman (M 9.1) earthquake, were preceded by what could be considered possible seismic and aseismic precursors, retrospectively.

In a recent study published in *Science* (20 July 2023), Quentin Bletery and Jean-Mathieu Nocquet presented results from the analyses of global high-rate global GPS time-series data from 3,026 geodetic stations in search of short-term precursory fault slip before large earthquakes. The statistical analysis of this data disclosed a subtle signal, aligning with a period of exponential acceleration of fault slip near the earthquake's hypocentre, starting roughly two hours before the rupture. These findings suggest that many large earthquakes initiate with a precursory phase of slip. The authors, however, caution that the current earthquake-monitoring instruments lack the necessary coverage and precision to detect or monitor for precursory slip at the scale of individual earthquakes.

Real-time Earth observation is now possible with satellite-based remote sensing techniques, and computing powers have increased multifold to conduct simulations and build predictive models of various Earth processes. Rapid strides in technology like Artificial Intelligence and its application in data analyses will certainly contribute to efforts in forecasting and mitigating natural hazards. We must be cautiously optimistic here, but recent advances in satellite-based observations and seismicity precursory observations like silent earthquakes before a great earthquake, at least along some of the subduction zones, augur well for prediction science.

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