Seismology 2000

AS we enter the new millennium, we are leaving behind a century that not only witnessed many devastating earthquakes, but also made great progress in understanding them. Although seismic wave detectors existed in China as early as AD 132, major advances in observational seismology took place only by late 1880s, when John Milne, James Ewing and Thomas Gray succeeded in developing a compact seismometer that could be installed in various locations around the globe. These instruments provided the earliest data on geographic distribution of earthquakes, leading to the recognition of plate boundaries. The body-waves recorded by these instruments were used for obtaining the first-order images of the earth's internal structure.

Three important developments during the second half of the last century helped rapid advances in seismology. First, in the 1960s, the US Government established a network of 120 seismic stations (WWSSN) in sixty countries, primarily to detect underground nuclear tests. Second, the advent of the theory of plate tectonics offered a clearer and conceivable framework for the basic dynamics of earthquakes. Third, computer technology opened up new possibilities to analyse a large amount of data. Deployment of three-component broadband systems in the later years further revolutionized data acquisition and interpretation of seismic data. As these systems became commonplace, seismologists were able to model earthquake processes and obtain source parameters and velocity structures, with higher resolution.

In parallel with the advances in earthquake recording and interpretation of seismic waves, many concepts that are fundamental to the understanding of earthquake processes were also developed during the early part of 20th century. In 1909, G. K. Gilbert noted that earthquakes not only follow a rhythm but they also alter positions, the earliest recognition of 'seismic gaps' as they are known today. A year later, following the 1906 San Francisco earthquake, Harry F. Reid proposed the elastic rebound theory, offering an explanation for the mechanism of earthquakes. The last quarter of the 20th century witnessed significant advances in geological characterization of earthquakes, leading to the concepts of fault segmentation, characteristic earthquakes and earthquake cycles. This period also witnessed the integration of geomorphological, geological and geophysical data, making the study of earthquakes more interdisciplinary. Radiometric dating techniques and stratigraphic and structural methods, considered far from the realm of traditional seismology, found their places in the study of earthquakes. Progress in strong motion studies; application of modern geodetic tools based on Global Positioning Satellites and SAR Interferometry have also complemented the study of earthquakes.

Despite the significant advances in seismology, several outstanding problems remain. From the societal point of view, the most frequently asked question is, can we predict earthquakes?. Optimism of 1970s following the prediction of the Blue Mountain Lake (1971) earthquake and the claimed success at Haicheng (1975) was short lived. As the window for the Parkfield earthquake closed with the expected earthquake failing to occur, the prevalent mood is that of skepticism. However, debates on the status of earthquake prediction continue (http://helix.nature.com/debates/earthquake). Prediction of individual earthquake remaining elusive, the challenge is to develop strategies for damage mitigation. On one hand, we need to develop models for earthquake recurrence, nucleation and fault interactions to identify potential source zones and on the other, we need to develop strategies to minimize damages. Seismological research in the coming years should be geared to achieve these dual goals. Papers in 'Seismology 2000' reflect how some of these ideas are being pursued by seismologists in India and abroad.

The biggest revolution in seismology is perhaps taking shape in the computer-based data management and exchange. A researcher who has no direct access to any seismic network can now acquire data from a variety of sources through the internet and create a Visual Seismic Network (VSN). Possibility for the transmission of data in real time at reasonable cost is what makes ventures like the US array project (www.earthscope.org), most exciting. The paper by Thomas J. Owens (**page 1201**) is about this 'democratization of seismology' and the revolution it will bring about, particularly in the investigations of continental lithosphere. As vast amount of data is being generated, the challenge before the seismologist is to develop software capabilities to manage and interpret the data. Owens touches upon this issue, very briefly.

The paper by Dapeng Zhao and J. R. Kayal (**page 1208**) is a fine example of the application of newer techniques of data interpretation. They use seismic tomography to obtain velocity images of the subducting Pacific slab and to study the velocity structure of the source zone of Kobe earthquake. Can the physical changes due to the redistribution of fluids or partial melt be imaged to infer temporal/spatial variations in velocity? In other words, can the snapshots of velocity changes be played in a sequence, to capture an earthquake in the making?

The paper by Ruth A. Harris (**page 1215**) also suggests the possibility of identifying potential source zones, based on the state of stress. Even as many aspects of earthquake mechanisms remain enigmatic, some of their interactions are being explained by simple calculations of stress changes. It is argued that stress shadows produced by great earthquakes act to suppress subsequent large earthquakes for times up to decades. For example, many parts of the San Andreas Fault are believed to be 'sleeping' in the shadows produced by the 1857 Fort Tejon and the 1906 San Francisco earthquakes. Perhaps, we do not understand the physics of earthquake nucleation and propagation well enough, to translate simple estimates of stress changes into formal earthquake prediction. If we did, the task of identifying source zones of impending earthquakes will be a lot easier.

Many gaps exist in our understanding of earthquake processes, even in locations where excellent data exists, and we are constantly revising our concepts. For example, our knowledge of earthquake periodicity was proved wrong at Parkfield, but the experiment contributed to our understanding of earthquake processes. This alone is a valid scientific justification for the continuance of the programme. The paper by Evelyn Roeloffs (**page 1226**) is an update of the Parkfield prediction experiment and the plans for future, which includes the operation of a borehole seismic cluster. With a probability of 1 to 10% per year higher than anywhere else in the US for a M 6 or greater earthquake, Parkfield should still be the world's best location to catch an earthquake live.

Seismicity data spanning long periods of time are essential for a thorough understanding of the earthquake phenomenon, especially to estimate recurrence intervals. Historical, archaeological and palaeoseismological data are now being used, to refine recurrence models. Scrutiny of historical records provides a better appreciation of the size and macro-seismic effects of earthquakes, which are useful for hazard assessment. While N. Ambraseys (**page 1237**) discusses the importance of historic database in the Himalaya, C. P. Rajendran (**page 1251**) explores palaeoseismic evidences for understanding recurrence in the Stable Continental Regions (SCRs). The paper by N. Ambraseys is a reappraisal of earthquakes in northern India during 1892–1912. He presents a new catalogue of earthquakes, with revised magnitude estimates. Where the historic data are vague, archaeoseismology and palaeoseismology are being used, to fill the gaps. Although palaeoseismology is widely applied in interplate regions, its use in the SCRs is rather limited. Studies in Australia and central and eastern United States have suggested recurrence rates ranging from hundreds of thousands to a couple of hundred years. How well do these estimates compare with seismogenic faults in other sites? C. P. Rajendran explores three earthquake source zones in SCR India, which seem to be characterized by varying styles of deformation and recurrence patterns.

Recent days have seen the use of many direct and indirect indicators of crustal deformation that complement historical and instrumental data. For example, measurements using the Global Positioning System (GPS) allow us to view the spatial and temporal distribution of strain changes in tectonically active areas. Although triangulation surveys in India began about two centuries ago, GPS based geodetic surveys have started only during the last decade. Roger Bilham and Vinod K. Gaur (**page 1259**) review the new developments and the way GPS geodesy has improved our understanding of the deformation process of the Indian subcontinent.

Three moderate earthquakes in rural India (Latur, Uttarkashi and Chamoli) during the last decade became severely damaging because of the poor construction – both in terms of design as well as quality of materials. Disaster-mitigation strategies for such regions must incorporate many components, starting with awareness programmes, development of economically viable and socially acceptable designs. Most international agencies involved in earthquake research have developed public outreach and educational programmes that are very simple and communicative (see www.usgs.gov; www.iris.edu, for example). Developing countries may need to develop appropriate methods to educate their less informed rural population; they must also develop and popularize safe and economically viable design codes. The paper by Anand S. Arya (**page 1270**) discusses some of these strategies that are being followed in India, and suggests measures for risk mitigation.

One way of presenting seismic hazard is through probabilistic seismic hazard maps, which communicate estimates of ground motions and frequency of occurrence. Modern instrumental data exist only for a few decades and the probabilistic estimates rely too much on statistical assumptions. More field observations and strong motion data from large earthquakes provide opportunity to validate some of these ideas. John G. Anderson *et al.* (**page 1278**) use the ground motion data from the Izmit (Turkey) and the Chi-Chi (Taiwan) earthquakes; evidence of precarious rocks and new results of physical and numerical modelling to evaluate the current methods of seismic hazard analysis.

With the increasing ability to predict ground motion and site response, buildings can be designed to withstand earthquake effects. Based on the probabilistic seismic hazard estimates, site characteristics and many other factors ranging from material availability to cost effectiveness, the engineer aims for the 'perfect' structure. Newer technologies in designs as well as building materials may eventually lead to that perfect structure. Durgesh C. Rai (**page 1291**) describes the future trends in earthquake-resistant designs – innovations in designs as well as shift to newer materials.

Establishing various facets of regional path effects is essential to understand how seismic waves are amplified as they propagate through the heterogeneous crust. Although these aspects of modelling regional wave propagation appear to be far removed from the central issues of seismic hazard, their usefulness for predicting ground motions has been well recognized. Chandan K. Saikia (**page 1301**) presents an efficient methodology for path calibration and determination of source parameters based on inversion of regional broadband seismograms of the Jabalpur (central India) earthquake.

Site dependency of earthquake damage, due to soil conditions and other characteristics is an important aspect in seismic hazard assessment. Microzonation is an important step in seismic hazard mitigation, particularly in large cities. Although these studies are in early stages in the Indian cities, it is now being recognized as an important aspect of urban planning. Sankar Kumar Nath *et al.* (**page 1316**) present early observations from an experiment in the Sikkim Himalaya where they have used receiver functions for microzonation.

It has been rather well accepted that many parts of the seismogenic crust are critically stressed and that small changes in strength introduced by loading/unloading of a reservoir can induce failure. Observations near some reservoirs have enriched our understanding of the role of faults/fractures in distributing fluids in the crust and altering pressure domains. Pradeep Talwani (**page 1327**) uses the example of seismicity at Monticello Reservoir to demonstrate that diffusion of fluid pressures is mainly responsible for inducing earthquakes. His paper also gives an update on the ongoing seismicity at Koyna.

The past decade was perhaps very expensive for India, in terms of losses in earthquakes. The devastating earthquake at Latur (Killari) that claimed more than 10,000 lives exposed not only the lack of earthquake preparedness, but also highlighted the need to strengthen seismic monitoring in the Indian shield. Two of the later events – 1997 Jabalpur and 1999 Chamoli – were less devastating; improvements in seismic instrumentation also enabled better studies of these earthquakes. Prantik Mandal *et al.* (**page 1334**) provide an update on these earthquakes; their source processes and mechanisms; it also highlights recent studies at Koyna.

In many ways, the Latur earthquake heralded a new era in Indian seismology. A major seismic instrumentation programme funded by the World Bank and liberal support from the Government of India through the Department of Science and Technology resulted in the upgradation of many existing seismic stations and installation of new broadband systems. Data processing and management have become more efficient through data centres at India Meteorological Department (IMD), Delhi and National Geophysical Research Institute (NGRI), Hyderabad. The paper by S. N. Bhattacharya and R. S. Dattatrayam (**page 1347**) provides an update of these efforts.

Advances in seismic monitoring have broken barriers of secrecy in nuclear testing. Just as the nuclear explosions get transparent, the scientific research also benefits, since these data find use in solving some of the fundamental problems in seismology. This is one aspect of monitoring nuclear explosions; the other is political. The Pokhran test of 11 May 1998 was conducted at a time when the US Government was encouraging countries including India to sign the Comprehensive Test Ban Treaty (CTBT). In the backdrop of these discussions, the Pokhran blast attracted tremendous international attention. Broadband data from the nearest GSN station (Nilore in Pakistan) were available to the international community to make independent assessments of its yield, some of which varied from the Indian estimates. In their paper, S. K. Sikka *et al.* (**page 1359**) reiterate their earlier estimates of yield.

India has always been a place of great interest to seismologists. R. D. Oldham's monograph on the great 1897 Assam earthquake is a classic document on earthquake effects. The 1819 Kutch earthquake is noted for the earliest well-documented observations of coseismic ground deformation. Some of the earliest geodetic observations were made in India more than a century ago, when a large discrepancy was noted between the astronomic and geodetic measurements in the Himalaya, leading to the theory of isostasy. India has made significant advances in seismological research and has evolved its own strategies in planning and implementing earthquake damage-mitigation programmes. The special section 'Seismology 2000' reflects some of the recent advances in seismological research in this country.

We had approached many researchers for contributions and the response was encouraging. Almost everyone kept their word and submitted papers on time and complied with the rather rigorous review process. The panel of reviewers included David Simpson (IRIS, USA); Donald V. Helmberger (California Institute of Technology, USA); Hans J. Küempel (University of Bonn); Jeffrey T. Freymueller (University of Alaska, USA); Joan Gomberg (US Geological Survey); P. L. Narula (Geological Survey of India); Pradeep Talwani (University of South Carolina, USA); Ravi Sinha (Indian Institute of Technology, Mumbai); Srikrishna Singh (Ciudad University, Mexico); S. K. Arora (National Institute of Rock Mechanics, Kolar); Sudhir K. Jain (Indian Institute of Technology, Kanpur) and S. P. Satyabala (National Geophysical Research Institute, Hyderabad). We thank them for their help in reviewing the papers.

This issue would not have materialized without the vision and encouragement of the editors of *Current Science* – Professors P. Balaram and S. Ramaseshan. We thank them for their support and hope that the papers presented in this special section will further stimulate earthquake research in India and abroad.

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