Towards Better Seismic Hazard Assessment: Need for an Integrated Approach

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Abstract

India exhibits a wide range of seismic zones with markedly different seismicity. The seismological characteristics of the 2000-km long active plate boundary region along the Himalayan front and the contiguous areas are very different from other active regions elsewhere in the country. The seismic hazard assessment of such a vast and tectonically complex region is not an easy task. The primary task is to generate high-quality data on seismic processes and ground motion. Very limited, empirical, near-field earthquake data exist in our country, and analytical models for strong motion are either non-existent or grossly inadequate for specifying details in a manner that is acceptable in earthquake-resistant design. Although the last ten years have witnessed tremendous improvement in the deployment of seismic instrumentation, the regional weak-motion and strong-motion accelerograph networks need to be expanded further, to obtain adequate information-base, in order to determine earthquake source mechanisms, regional seismic attenuation, and local ground response. Better geological and geophysical data are needed to constrain the earthquake destruction potential, upper-bound magnitude in different geographic regions, and to assess the dynamics of faulting and recurrence intervals for specific faults. The immediate need is to transform the existing seismic zoning map into a first-order probabilistic hazard map. This paper focuses on the status of seismic hazard assessment in India, their inherent limitations, and what needs to be done to acquire the ideal database for meaningful hazard assessment.

Introduction

Earthquakes lead the list of natural disasters in terms of damage and human loss, and they affect very large areas, causing death and destruction on a massive scale. The Indian landmass, a complexly deforming part of Asia, has generated a large number of destructive earthquakes in the recent past. The seismic source zones in India reflect this complexity and show marked variations in their faulting behaviour, and the resultant seismicity. The plate boundary regions – including the Himalayan frontal areas, northeast India, and the Andaman Nicobar Islands – have been identified as capable of generating very large earthquakes (Plate 9; Table 1). Among these, the largest earthquake occurred near the Shillong Plateau in 1897 (Oldham, 1899), which reportedly had a magnitude of 8.7 with ground acceleration exceeding 1.0 g.

Table 1 Damaging earthquakes in India during the last two centuries

Year	Location	Tectonic setting	Magnitude	Comments
1819	Kachchh	Ancient rift	7.5	Over 2000 people killed; significant changes in the landforms, including the formation of the 90-km-long Allah Band
1897	Assam	Himalaya	8.7	Investigated by R D Oldham; a classic document in seismology. Widespread damages in NE India; over 1,600 deaths. Recalibrated magnitude Mw 8.01 (Ambraseys, 2000)
1905	Kangra	Himalaya	8.6	Loss of life estimated as 19,000; Recalibrated magnitude Mw 7.8 (Ambraseys, 2000)
1934	Bihar–Nepal	Himalaya	8.3	Over 10,000 deaths and widespread damage
1935	Quetta	Himalaya	7.6	Over 30,000 deaths. The site is now in Pakistan
1950	Upper Assam	Himalaya	8.7	Over 1500 deaths; 40–50% of the existing wildlife perished. Severe landslides and changes in river courses occurred
1967	Koyna	Peninsular Shield	6.3	200 lives lost; one of the 4 reservoir-induced earthquakes of M>6
1991	Uttarkashi	Himalaya	6.5	Killed over 1000 people; severe to partial damage to about 0.1 million houses
1993	Killari	Peninsular Shield	6.3	Killed over 10,000 people. Destroyed > 0.2 million houses in typical rural settings
1999	Chamoli	Himalaya	6.8	About 100 dead; better construction saved many houses
2001	Bhuj	Ancient rift	7.6	Over 20,000 people died. The largest earthquake in an urban setting in modern India. Many multi-storied houses collapsed. It also affected the distant city of Ahmedabad.

Peninsular India, which a part of the Precambrian shield, also had its share of damaging earthquakes, although they were of lesser magnitude, the largest being of mb 6.3 at Koyna and Killari. The seismic potential of the Precambrian crust is not uniform, but varies according to the degree of rifting or crustal extension that it had undergone in the geologic past (Johnston, 1995). Our understanding of the source processes in the shield region is rather sketchy, and still we do not have a coherent theory of their genesis. A much-quoted example of such an earthquake is that of the 1993 Killari (Latur), which occurred in the unrifted part of the Peninsular India. Although of moderate magnitude (Mw 6.3), it devastated several villages and killed more than 10000 people (Gupta, 1994). Such regions, which are quite far from plate interactions and associated deformation fields, are generally considered to be relatively free from large (M>7.0) earthquakes. However, due to the rarity of earthquakes, even a moderate quake can be damaging in these areas, because most man-made structures are neither planned nor designed to cope with the expected ground tremors. The recent example of the earthquake at Bhuj is a classic case associated with an ancient rift in a continental setting. The source zones in the rifted areas are capable of generating large earthquakes (M>7.0), possibly with shorter recurrence intervals (Rajendran, 2000).

These earthquakes occur unexpectedly along little-known faults in areas that are least prepared to deal with such events, creating unprecedented panic and extensive damage. Although the damaging potential of an earthquake is dependent on its magnitude, location and, indeed, the time of its occurrence, the site conditions and the local building practices have been the major causative factors that increase its destructive capacity (Arya, 2000). The 1993 Killari and 2001 Bhuj events are typical examples that illustrate how the factors such as poor site conditions and inappropriate local building practices can increase the destructive potential of earthquakes. If the earthquake was totally unexpected at Killari, it was not so in Kachchh. The post-seismic surveys conducted there have made it amply clear that the lack of preparedness, in terms of siting and design of structures, was an important factor that intensified damages due to the 2001 Bhuj earthquake (Mw 7.7) (Rajendran *et al.*, 2001). Although the Bhuj region falls in the highest risk zone (Zone V; Plate 9), and it had experienced a similar large earthquake in the past (the 1819 Rann of Kachchh) and a moderate one in 1956 (Anjar), the level of awareness and preparedness in and around Bhuj was surprisingly quite low.

Since the occurrence of the Killari earthquake in 1993, there has been a concerted effort to upgrade the seismic instrumentation in the country for increasing the earthquake-monitoring capabilities. There have been tremendous efforts made in deploying instruments and generating expertize in broad-band seismology, but much remains to be done in terms of data management — translating these data for better earthquake hazard and mitigation strategies. This article reviews the current scenario in India and outlines some of the basic inputs required for an action plan for a more realistic seismic hazard assessment.

Seismic Zoning Map of India: Limitations

The institutionalized work on seismic zoning of the country was initiated by the Indian Standards Institution (now called the Bureau of Indian Standards, BIS) in the year 1960, based on the isoseismal maps of various damaging earthquakes prepared by the Geological Survey of India (see Narula, 1996). The codification of standards for earthquake-resistant design of structures was also initiated and the first seismic zoning map was included in the code IS: 1893–1962. The standard practice was to plot the intensities of different earthquakes, i.e., to divide the whole country into various zones, which have experienced a particular intensity during the past earthquakes; later the same hazard level was projected for future earthquakes. The presently available map divides the country into five seismic zones, V to I, based on the various probable maximum intensities on a decreasing scale (Plate 9).

Although the available zoning map provides some basic information on the relative seismic potential of various regions in the country, it has several limitations. Mainly, it is constrained by incomplete data on past earthquakes, insufficient scientific methodologies and lack of proper understanding of the source mechanism of earthquakes (Narula, 1996). The history of earthquake recording and the historical documentation itself are too short to represent the long-term activity of the faults. Thus the time window for deriving desired confidence levels by statistical methods is too short, particularly for large-magnitude earthquakes, which would release large strain at one time that has accumulated over a long period. Studies in the Indian shield region and elsewhere compel us to assume that earthquakes at any one source have fault-specific repeat periods (Crone *et al.*, 1997; Rajendran, 2000). In all these areas, an important issue is to estimate how much time has elapsed since the last earthquake. That requires us to know whether the faults in question are at the early phase of a deformation cycle or at its late stage. Considering the variable recurrence intervals on different faults, we may be dealing with near chaotic behaviour of faults, when one truant fault may generate an 'out-of-the-blue' earthquake. This has been amply demonstrated by the Killari earthquake of September 1993, which occurred in Zone I shown in the seismic zoning maps as a low damage risk zone (MSK V). This is an area where no neotectonic activities or any active faults were observed, previously. Several problems seem to hamper identification of potentially active faults in these areas and some of them are listed below:

1. Because of the faster erosion rate in comparison with the rate of deformation, surface expressions of faults may be poorly developed.
2. Hidden seismogenic (blind) faults may not have clear surface expressions.
3. Even where the faults are exposed, the time of previous movement is generally not known. In other words, our inventory of active faults is far from complete.

The occurrence of the Killari earthquake exposed the inadequacy of the seismic zoning, raising questions on the presumed stability of other areas that fall in Zone I. The assumption that areas of previous large earthquakes would be potential locales for similar future earthquakes is inherent in the concept of zonation. Since the seismic zoning map is based on limited data of past earthquakes, it does not fully reflect distribution of active structures that hold potential for future earthquakes that remain unrecognized due to reasons discussed above. Nor does it incorporate the concept of elapsed time, which comes from the knowledge of timing of the last faulting episode and recurrence rate of individual faults. Thus, the existing seismic zoning strategy is primarily constrained by incomplete databases, especially in regions where seismic intervals are much longer than the historic records. Besides, significant gaps in the data exist, with regard to effects of earthquakes (ground shaking, structural responses, etc.). Site-specific data on ground acceleration, soil conditions and liquefaction potential are either not available or often overlooked.

In what may be the first of its kind in India, Khattri *et al.* (1984) prepared a probabilistic seismic hazard map of India showing peak ground acceleration having a 10% probability of being exceeded in 50 years. Recent attempts at generating a seismic hazard map of India based on the computation of probabilities of occurrence of ground motion in a given time period, as a part of G-SHAP programme (Bhatia *et al.*, 1999) is another worthwhile step in this direction. Although the aforementioned probabilistic maps are significant improvements on the zoning map, they still lack many fundamental inputs. For example, the non-availability of representative strong motion–attenuation relationship is a serious constraint. Recently, an attempt has been made to generate a first order seismic hazard map of the country using a deterministic approach based on the computation of synthetic seismograms (Parvez *et al.*, 2001). All of these maps, however do not reflect site-specific data on soil thickness and amplification of seismic waves (site responses), which would have maximized their applicability (e.g., El-Araby and Sultan, 2000).

In this article, we delineate some of the essential inputs that form the basis of a first order earthquake hazard quantification in the country. This will have direct bearing on the hazard assessment, risk analysis and also address the public safety concerns. We emphasize the need for an integrated approach to seismic hazard assessment which will include identification and locations of active faults or potentially active faults, information on maximum credible earthquake (maximum earthquake potential) in a region, recurrence periods, probabilities of exceedance of ground motion and local site effects such as soil-related amplification, soil liquefaction and ground failure effects induced by proximity to fault zones. We suggest that these inputs may be integrated using a geographic information system (GIS) to produce a comprehensive seismic risk map of the country.

Seismic Hazard Assessment: Inputs

Seismotectonics

Detailed geological and tectonic maps delineating seismotectonic provinces will provide the basic inputs for seismic hazard zonation. These data must show age of rocks, composition and structural configuration of different materials as well as large-scale tectonic features. Whether the regions in question are characterized by exhumed crystalline rocks or basins containing sediments, and the nature and thickness of sediments and their evolution are to be ascertained for delineating specific tectonic provinces. Interpretation of surface landforms may often provide useful information on the nature and pattern of tectonic activity in relation to tectonic surfaces. Tectonic studies must also bring out the duration of processes that have led to the current configuration and whether these processes are currently active. For example, an active rift is governed by the ongoing extensional processes, but ancient rifts may only have the imprint of past tectonic activity related to rifting processes, which will have a bearing on their current seismogenic characteristics.

Neotectonic processes in the Proterozoic mobile belts and known shear zones, which are prone to reactivation, is another area that needs urgent attention. The most recent worthwhile effort in this direction is the *Seismotectonic Atlas* (Geological Survey of India, 2000), which has presented a comprehensive picture of the faults and lineaments of the country, together with spatial distribution of earthquakes from historic times. Although this map provides the basic information on the faults with regard to their orientations and distribution of earthquakes, the gaps in seismicity data as well as poor knowledge of subsurface features make this picture rather sketchy.

Recent Seismicity

Seismological data provide the pattern of contemporary seismicity and epicentral distribution, which is a basic input in hazard assessment. After the Killari earthquake in 1993, much effort has gone into the establishment of a number of broadband seismic stations in the country. Together, these stations will provide better earthquake detection and location capability. These facilities will now generate data that will give tremendous boost to meet the objective of accurate estimation of earthquake parameters. High quality boradband data will provide more precise source parameters including epicentre, focal depth, source mechanisms and dimensions, magnitude, stress drop, seismic moment, rupture velocity and attenuation characteristics. Efforts are also underway to increase the spatial distribution of these instruments so that we will have an optimal network in the country (Kelkar *et al.*, 2002). Along with these initiatives, efforts should also be undertaken to improve the historic seismicity database and updating of catalogues (e.g., Ambraseys, 2000). A strong database of temporal and spatial distribution of earthquakes within different seismognic provinces along with their will-determined magnitudes will greatly improve the confidence in statistical regressions using the frequency-magnitude relation.

Paleoseismicity

While historical data provide information on past earthquakes only for a few centuries back in time, the more recent technique of paleoseismology can turn the clock back to several thousands of years, to obtain the timing and frequency of past events (McCalpin, 1996). Paleoseismological interpretations of trench exposures provide information about recurrence rates on faults, the magnitudes of past earthquakes, time since last earthquake, and the slip rate (e.g., Crone and Wheeler, 2000). Most importantly, this geological information can provide a better insight into the source of the earthquake. Paleoseismological studies have been initiated in various parts of the country, and we have now started to appreciate the variability of faulting behaviour even within the same tectonic domain (e.g., Rajendran, 2000).

The potential of using geological data to study earthquake processes is still not fully exploited. Using these techniques, we should be able to build a good database on those past earthquakes with no instrumental recordings or historic documentation. The information on fault lengths, type of displacements, and the faulting mechanism in a particular domain can be used to develop empirical models. For example, the relation based on global data by Wells and Coppersmith (1994) states that $M=5.08 + 1.16 \log (SRL)$, where M is the movement magnitude and SRL is the surface rupture length of the fault. These relations can be used for estimating the maximum earthquakes and incorporating them into probabilistic ground-motion maps or they can be used to forecast the probability of the next earthquake during a chosen time interval. The important questions on direction, length and type of faulting during an earthquake can be resolved by supplementing geological information with instrumental data.

Crustal Deformation

During the period between successive earthquakes, the ground near the fault deforms in response to the stress build-up. In addition, the magnitude of deformation depends on the physical properties of the crustal material. The GPS-aided geodetic studies in India are in their initial stages. This geodetic data will provide information on the location, orientation, and rate of accumulation of crustal strain in a particular region. By employing high resolution GPS (Global Positioning System)-based geodetic studies, subtle deformations can be monitored, even where the fault is buried. Such measurements are useful to study the pre-seismic deformation, to deduce the location and orientation of hidden faults, and to estimate the slip due to an earthquake. The GPS surveys also help in identification of regions of high stress. One of the more recent examples is the use of this technique in the Himalaya region (Bilham *et al.*, 1997). Quantitative data on the regional stress regime and the orientation of stress axes provide other useful inputs to model deformation in a region. Although *in situ* stress measurements give more accurate data, they are fewer and do not represent the actual state of stress at the seismogenic depths. Generalized stress maps based on geological data, *in situ* stress measurements, as well as good quality focal mechanism solutions, will provide a reasonably good picture of the regional stress field (Zoback, 1992). One complementary new technique called "space-based synthetic-aperture radar interferometry" is now being increasingly used for mapping the deformation of the ground around the fault, before and after the earthquake. The two scans, representing the precise distance between the satellite and the ground, are digitally subtracted one from the other to obtain the amount by which the ground has moved (represented by coloured bands called 'interference fringes'). We need to identify potential areas where these techniques can be used to monitor deformations that are associated with faulting.

Geophysical Data

Geophysical data allows determination of the nature and configuration of the earth at depths that are not directly observable from the surface. Gravity and magnetic anomalies, and seismic reflection data are often used to obtain images of the subsurface. These techniques are particularly useful in regions where thick sedimentary cover conceals the basement structures. Although regional geophysical surveys have been conducted by various Indian agencies, much remains to be done across the faults, in a manner that will resolve the nature and style of deformation. For example, geophysical methods including seismic reflection have been used extensively to map the subsurface features in the New Madrid seismic zone, in the United States where three large earthquakes occurred in 1811 and 1812 (Schweig *et al.*, 1992; Braile *et al.*, 1997). Similar studies may be very useful to map the subsurface structures and to model fold growths in the ancient rift zones, like those in Kachchh.

Ground Motion Data

The estimation of expected ground motion at a given distance from an earthquake of given magnitude is a fundamental input to earthquake seismic hazard. For example, during the recent Bhuj earthquake, the city of Ahmedabad that is about 250 km away from the source of the earthquake, suffered serious damage. Possible ground-motion effect due to a local or a regional earthquake needs to be estimated. This applies to many large cities in India, including Delhi. And this brings into focus the importance of site effects in amplifying seismic energy.

The determination and quantification of seismic design criteria for engineered structures depends on the estimates of expected ground motion during the lifetime of the structure. These estimates are expressed as attenuation relationships that express peak ground acceleration (PGA) as a function of distance. Empirical relations based on recorded ground acceleration, as well as theoretical models, are often used to develop attenuation relations. The most commonly mapped ground motion parameters are: horizontal peak acceleration (PGA); peak ground velocity (PGV), and 5% damped spectral acceleration (SA) for a given site (e.g., Abrahamson and Shedlock, 1997). Numerical models are widely used to obtain estimates of peak acceleration at distances (e.g., Hays, 1980; Joyner and Boore, 1981). Therefore, efforts must be made to develop appropriate relations for various regions within the country. A major stumbling block in ground-motion studies in India is the lack of strong-motion data on a regional scale. This situation calls for the establishment of a number of accelerographs. While it may be possible to generate empirical relations for the active regions of Indian subcontinent, they may have to be numerically simulated for the shield region. A template for such an approach has already been made for the state of Maharashtra (Seeber *et al.*, 1999). There is an urgent need for developing better strong-motion database and attenuation relation, which, in turn, is related to growth in local expertise in strong-motion seismology.

Site Effects

It has been observed that severe damage due to many earthquakes tends to be concentrated in discrete zones, which may be separated by relatively unscathed regions. The localization of damages due to ground shaking has been attributed to the local physical conditions, which includes nature sediment cover (silt/clay content), and the depths of water tables and basements.

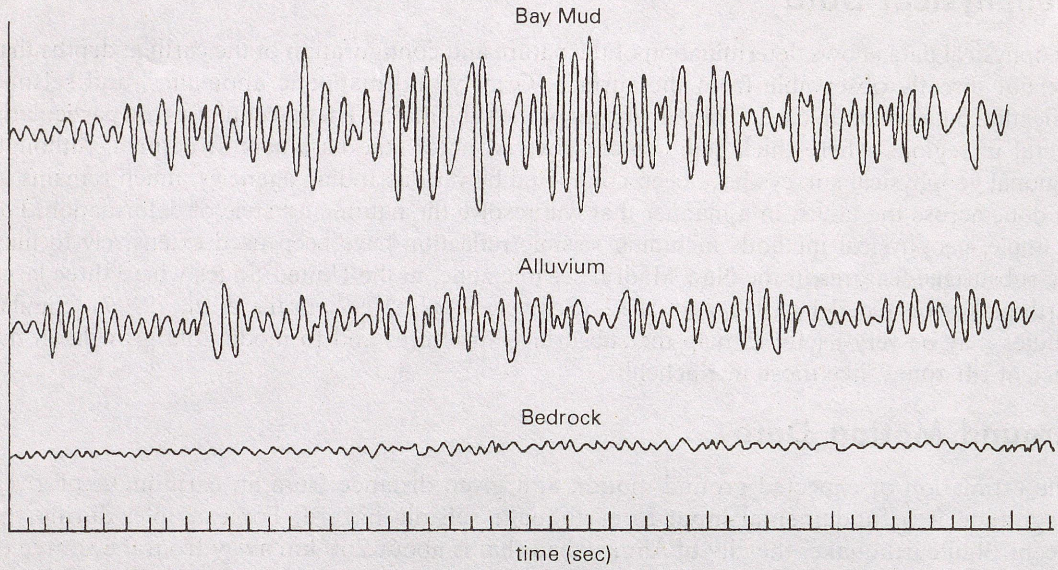

Figure 1 Horizontal ground motions of an underground, unclear explosion, recorded by accelerographs in San Francisco, passing through different materials (after Borcherdt, 1975). The vertical scale is arbitrary. The idea is to show the relative magnification.

It has been demonstrated that the ground velocity amplifications are many times greater in sites underlain by thick sedimentary cover (Figure 1). The most striking illustration of amplification of seismic waves, resulting in heavy damage, was seen during the 1985 (Ms 8.1) Mexico earthquake. Heavy damages in Mexico City were found to be concentrated in areas of thick substratum (40 m) of lake-deposits (Singh *et al.*, 1988). The thickness and geotechnical properties of the soil, and the nature of the underlying rock and frequency content of seismic waves, are some of the factors that govern the site amplification (e.g., Nakagawa *et al.*, 1996).

In areas where the soil is saturated with water and where the water table is shallow, large ground acceleration can cause liquefaction of soil and ejection of soil and water. For example, soil liquefaction was the primary cause of damage during many earthquakes (e.g., 1964 Niigata (Japan), 1994 Kobe (Japan) and 2001 Bhuj). In order to understand the hazard posed by liquefaction, we need to generate liquefaction susceptibility maps, using surface and subsurface geotechnical and sedimentological data.

The identification of zones that are most subject to severe hazards, based on the local site conditions, refines the hazard map and this is what is attempted in microzonation. Although this is a fairly new concept, data are being collected at various locations in India for microzonation (Nath *et al.*, 2000; Iyengar, 2000; Parvez *et al.*, 2002). As urban centres expand and more development takes place around major cities, this exercise must progress so that the new structures can be designed to withstand the expected ground tremors.

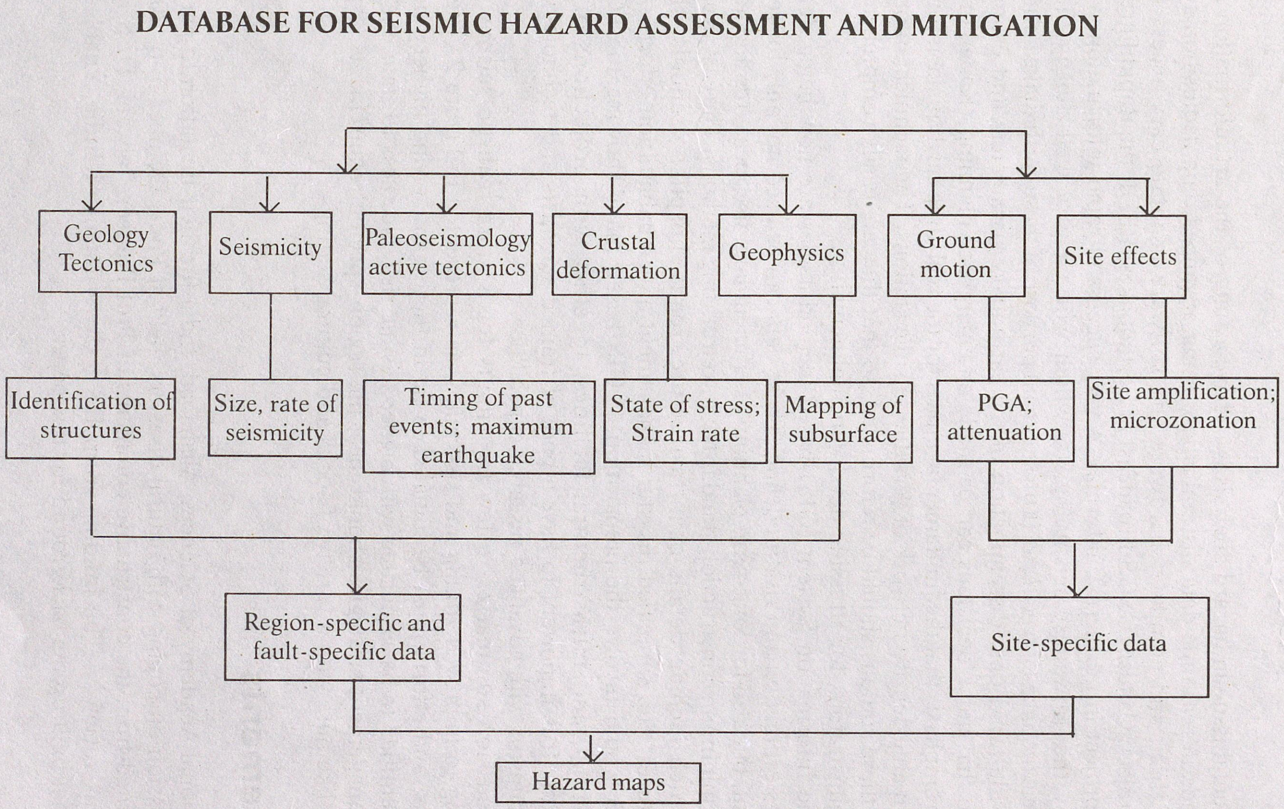

Figure 2 The relationship between data inputs for seismic hazard assessment and mitigation.

Strategy for an Integrated Hazard Assessment and Mitigation

The most fundamental issue in hazard analysis is to have a state-of-the-art information system. Recent global trends in real-time data dissemination, using advanced data acquisition systems, digital communication, and computer hardware and software facilitate easy access to data (e.g., the CUBE project: Caltech/USGS Broadcast of Earthquakes; REDI: the Rapid Earthquake Data Integration project in northern California). A very successful rapid information system is being operated by the Taiwanese seismologists, which worked very well during the 1999 Chi-Chi (Taiwan) earthquake (Wu *et al.*, 2000). The main purpose of these earthquake information systems is to provide rapid data dissemination of the earthquake parameters and estimates of ground motion, so that quick decisions can be made on emergency planning (Kanamori *et al.*, 1997). It needs no emphasis that the fundamental inputs for the real-time earthquake information systems come from an extensive network of versatile seismic stations. The technical information gathered through these stations should be reformated, so that they are easily comprehensible to planners and administrators, for stressing developmental activities.

The Geographic Information System (GIS)-based methodologies are now being developed for earthquake-loss estimation and risk modeling. These data can be used not only for real-time damage assessment, but also for long-term planning of efficient land use measures and adoption of building codes (minimum construction standards), or retrofitting methods. The easy availability of such maps, which include details of infrastructure, roads, hospitals, schools, shelters, engineering structures, etc. simplified disaster management and rehabilitation efforts. A more rigorous approach would involve the preparation of GIS-based maps showing the PGA and liquefaction potential, and infrastructural facilities, together with projections of future developmental plans. It is important to have a pool of trained scientists and technologists and institutional mechanisms with advanced research capabilities.

The above discussion summarizes a few key inputs for a more realistic seismic hazard assessment, leading to improved zoning and risk maps, as represented in Figure 2. There may be many data gaps, and efforts must be initiated to fill in these gaps, giving higher priority to regions already identified to be associated with higher seismic risk. Needless to state, the hazard mitigation and management strategies should meet the region-specific requirements, especially in a large country like ours with a variety of social and cultural settings.

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