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ORIGINAL RESEARCH PAPER

Earthquake safety in India: achievements, challenges and opportunities

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Abstract The Indian subcontinent has suffered some of the greatest earthquakes in the world. The earthquakes of the late nineteenth and early twentieth centuries triggered a number of early advances in science and engineering related to earthquakes that are discussed here. These include the development of early codes and earthquake-resistant housing after the 1935 Quetta earthquake in Baluchistan, and strengthening techniques implemented after the 1941 Andaman Islands earthquake, discovered by the author in remote islands of India. Activities in the late 1950s to institutionalize earthquake engineering in the country are also discussed. Despite these early developments towards seismic safety, moderate earthquakes in India continue to cause thousands of deaths, indicating the poor seismic resilience of the built environment. The Bhuj earthquake of 2001 highlighted a striking disregard for structural design principles and quality of construction. This earthquake was the first instance of an earthquake causing collapses of modern multi-storey buildings in India, and it triggered unprecedented awareness amongst professionals, academics and the general public. The earthquake led to the further development of the National Information Centre of Earthquake Engineering and the establishment of a comprehensive 4-year National Programme on Earthquake Engineering Education that was carried out by the seven Indian Institutes of Technology and the Indian Institute of Science. Earthquake engineering is a highly context-specific discipline and there are many engineering problems where appropriate solutions need to be found locally. Confined masonry construction is one such building typology that the author has been championing for the subcontinent. Development of the student hostels and staff and faculty housing on the new 400-acre campus of the Indian Institute of Technology Gandhinagar has provided an opportunity to adopt this construction typology on a large scale, and is addressed in the monograph. The vulnerability of the building stock in India is also evident

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from the occasional news reports of collapses of buildings under construction or during rains (without any earthquake shaking). Given India's aspirations to be counted as one of the world's prosperous countries, there is a great urgency to address the safety of our built environment. There is a need: to create a more professional environment for safe construction, including a system for code enforcement and building inspection; for competence-based licensing of civil and structural engineers; for training and education of all stakeholders in the construction chain; to build a research and development culture for seismic safety; to encourage champions of seismic safety; to effectively use windows of opportunity provided by damaging earthquakes; to focus on new construction as opposed to retrofitting existing buildings; and to frame the problem in the broader context of overall building safety rather than the specific context of earthquakes. Sustained long-term efforts are required to address this multi-faceted complex problem of great importance to the future development of India. While the context of this paper is India, many of the observations may be valid and useful for other earthquake-prone countries.

Keywords India · Earthquake engineering · Seismic safety · Capacity-building · Historical developments · Confined masonry · Codes · Licensing

1 Introduction

It is my great honour to have been invited to be the 15th Mallet-Milne Lecturer, giving a lecture named after such pioneers in the field. I hope to build on the work of some previous Mallet-Milne lecturers, who have so eloquently discussed the problem of earthquake safety around the world. From my mentors, George Housner and Bruce Bolt, second and fifth Mallet-Milne lecturers respectively, who passionately tackled global engineering and science problems, I have learned much and am privileged to be following in their footsteps. Two more recent Mallet-Milne lecturers, Robin Spence and Roger Bilham, have persuasively argued that earthquake risk is "growing, not shrinking", predominantly in the cities of the developing world. I hope to bring new insights to the problem they have articulated. In my lecture I will discuss the earthquake risk in one particular country, my own, India, where I have been involved in earthquake engineering for my entire career. While as a country we have made tremendous strides in some areas, the problem remains enormous, with much to do. I will discuss historical developments of earthquake risk reduction in India, the progress made in recent years, and the challenges that lie ahead to reduce earthquake risk. While the context of this lecture is India, many of the observations may be valid and useful for other earthquake-prone countries.

The Indian subcontinent has suffered some great earthquakes with magnitude exceeding 8.0. The earthquakes of the late nineteenth and early twentieth centuries triggered a number of developments in India towards science and engineering related to earthquakes, including the development of construction practices that are robust against earthquake shaking. The institutionalization of earthquake engineering in the country took place as early as the late 1950s with teaching and research in earthquake engineering starting at the University of Roorkee (now IIT Roorkee).

Despite these early developments towards seismic safety, moderate earthquakes in India continue to cause thousands of deaths, indicating poor seismic resilience of its built environment. The first seismic code was developed and implemented after the 1935 Quetta earthquake for reconstruction in Baluchistan (now in Pakistan) (see Jain and Nigam 2000), and the first national seismic code was developed in 1962 (IS 1893 1962). And yet, effective implementation of the building codes remains a major challenge.

The 2001 Bhuj earthquake was the first instance of an Indian earthquake causing collapses of modern multi-storey buildings, since the earlier earthquakes had occurred in rural or semi-urban settings. Approximately 14,000 deaths (Jain 2002) in this earthquake created unprecedented awareness amongst professionals, academics and the general public, and opened up a number of windows of opportunity for capacity-building for seismifc safety.

The National Information Centre of Earthquake Engineering (NICEE), set up at the Indian Institute of Technology Kanpur in 1999 to meet the needs of the country in terms of "information" on earthquake engineering, was able to kickstart its activities in a very receptive environment after the 2001 earthquake. Currently, NICEE continues to undertake a number of capacity-building activities by publishing and disseminating information, and by increasing awareness among architecture and civil engineering students, academics and professionals through conferences and workshops.

During 2003–2007, a comprehensive National Programme on Earthquake Engineering Education (NPEEE) was implemented by the seven Indian Institutes of Technology (IITs) and the Indian Institute of Science (IISc) with financial support from the Ministry of Human Resource Development (MHRD), Government of India. It enabled more than 1000 teachers of civil engineering and architecture to receive training in earthquake engineering through short courses, conferences, seminars and research programmes. The programme also supported development of curricula, resource materials and teaching aids, and the development of library and laboratory resources. As a result of NPEEE, a large number of civil engineering and architectural colleges now teach concepts of seismic engineering to their students.

Both NICEE and NPEEE were effective because of the groundwork that had already been put in place, and because the 2001 Bhuj earthquake provided the right environment to push forward with these two initiatives. India has made a lot of progress towards awareness and capacity-building in the last two decades, and this is particularly visible when one compares the situation with respect to other developing countries in general and with the neighbouring countries of the subcontinent in particular. However, if India were to be measured against its aspirations of counting amongst the world's leading countries in terms of earthquake safety, our progress has been quite inadequate.

One area of major concern is the lack of a professional environment to ensure safe construction; here the term 'safe construction' is being used in a broad sense and not just in the narrow context of seismic safety. The country has neither a system for code enforcement, nor competence-based licensing of civil or structural engineers. Enforcement of codes is closely connected with quality of governance at the local city level, and much remains to be done towards this.

Earthquake engineering is a highly context-specific discipline. Practices and concerns of one country or one society may not be effective elsewhere. Interventions for seismic safety must account for local construction practices and building materials, capacity and nature of the local construction industry, and the local geological and seismological setting. Further, there are many engineering problems that may be specific to a region and appropriate solutions must be found for the same locally. For instance, new seismically resilient building typologies may need to be evolved that meet the local needs in terms of local building materials, practices and weather conditions. *Confined masonry construction* is one such building typology that my colleagues and I have been championing for the subcontinent. Development of a new 400-acre campus for the Indian Institute of Technology

Gandhinagar has provided an opportunity to adopt this construction typology on a large scale.

It is not possible in one lecture to provide comprehensive coverage of all that has happened and is happening in India in terms of earthquake safety. There are many people in the country, in academia, practice, government and the NGO sector, who are all doing good work. Hopefully I touch upon some of these activities in my remarks, but the focus of my lecture is on work with which I have been involved. And of course much of my work has been conducted with a number of my colleagues who are passionately engaged in reducing seismic risk. We all recognize this is a daunting challenge with an enormous urgency, considering the huge populations that are at risk.

2 Seismic hazard and risk

2.1 The geotectonic setting of the Indian subcontinent[1]

The geology and geography of the Indian subcontinent is rather complex and consists of three main sub-divisions: the Himalayas, the Indo-Gangetic Plains, and the Peninsula (Fig. 1). The Himalayas have been formed as a result of the collision of Asia with India and are rather young mountains. The front edge of the northward moving Indian plate consists of ocean sediments resting on hard basement rocks. As a result of intense compression at the boundary, there has been repeated folding and faulting, and melting in the deeper parts. The Indo-Gangetic plain has been formed by recent alluvium brought by three mighty river systems, the Indus, the Ganges and the Brahmaputra, depositing these sediments across densely populated areas in Sindh (in Pakistan), Punjab, Uttar Pradesh, Bihar, Bengal (including Bangladesh) and Assam. The Peninsula consists of rocks of very early ages (Precambrian), with large parts of the western and central Peninsula covered by lava flows of the Deccan Traps.

The Himalayan range covers Baluchistan on one side and Myanmar on the other, with significant bends and curvatures in the range. The mountain range rises steeply from the Indo-Gangetic Plains and only gently slopes towards Tibet. The Outer Himalayas (Siwalik Ranges) in the southern zone have elevations up to 900 m. The Middle or Lesser Himalayas have elevations up to about 3200 m, and the Great Himalayas (also termed Inner Himalayas) have elevations ranging from 3000 to 8000 m. The region north of the Great Himalaya is Tethys Himalaya with an elevation ranging from 3000 to 4200 m. The northern edge of the Tethys Himalaya is the collision zone of the Asian and the Indian Plates (Fig. 2). Tibet and Karakoram, to the north of the Tethys Himalaya, are part of the Asian Plate and have an elevation of about 5000 m. Parallel fault systems separate the zones: Indo-Gangetic Plains and the Outer Himalaya are separated by the Himalayan Frontal Thrust (HFT), Outer Himalaya and Lesser Himalaya by the Main Boundary Thrust (MBT), and Lesser Himalaya and Great Himalaya by the Main Central Thrust (MCT) (Fig. 3). The Trans Himalayan Fault separates the Great Himalaya from the Tethys Himalaya, and the junction of the Tethys Himalaya and Tibet is known as the Indus-Tsangpo Suture. The rivers have eroded huge amounts of sediments and transported these along their course, and deposited these in the trough between the mountains and peninsular India to form the Indo-Gangetic Plains.

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[1] Much of the material in this section draws from unpublished material by the late Bruce Bolt and the author, with comments by K. S. Valdiya, as well as published works of Valdiya (1998, 2010).

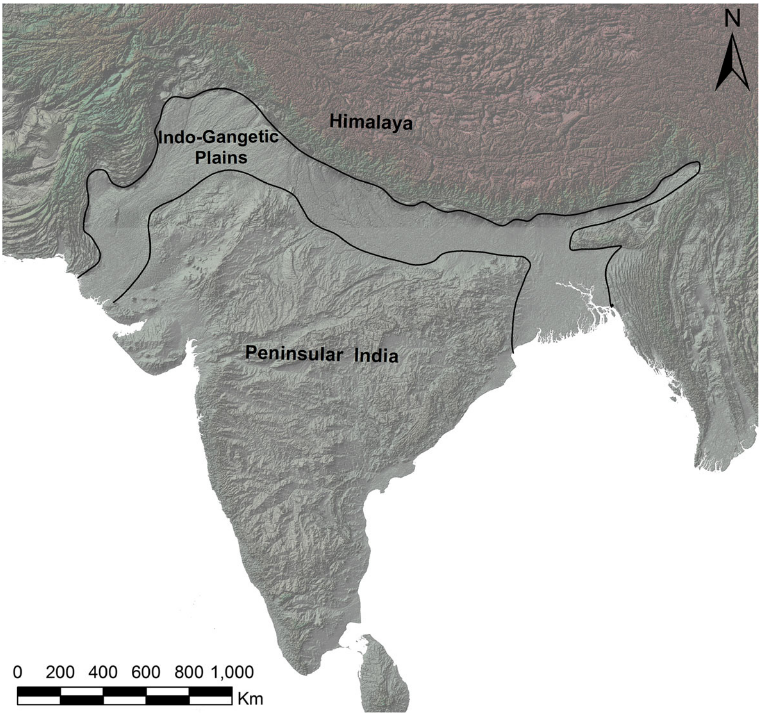


Fig. 1 Three main sub-divisions of Indian subcontinent namely Peninsular India, Indo-Gangetic Plains and the Himalaya (*courtesy*: Vikrant Jain)

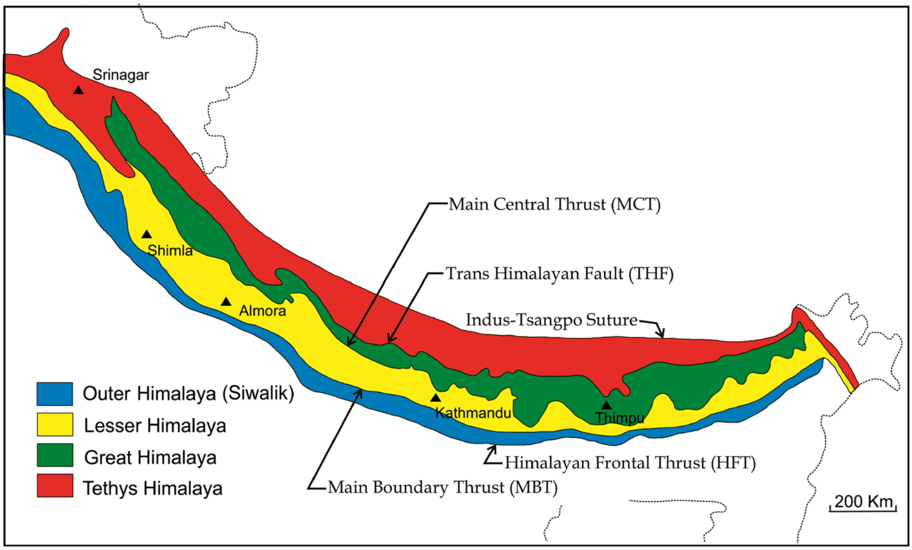


Fig. 2 Major litho-tectonic units of the Himalaya (Modified after Valdiya 2010)

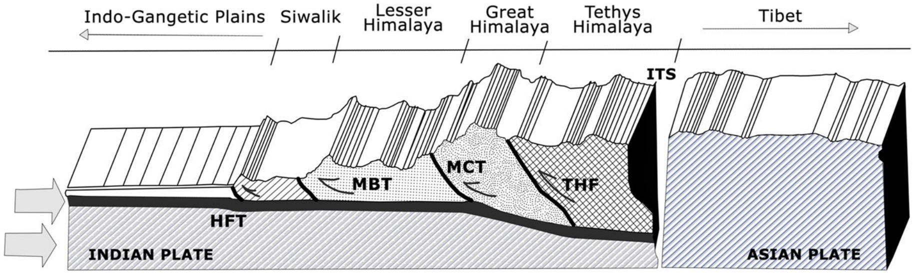


Fig. 3 Typical cross-section across the Himalaya showing major litho-tectonic units. (*HFT* himalayan frontal thrust, *MBT* main boundary thrust, *MCT* main central thrust, *T-HF* trans himalayan fault, *ITS* indus-tsangpo suture zone) (Modified after Valdiya 1998)

There has been a regular occurrence of great earthquakes in the Himalayas and currently most of the seismic activity is located south of the Main Central Thrust (MCT). The Himalayan Frontal Thrust is believed to be the likely location of future great earthquakes. Because of its proximity to the densely populated Indo-Gangetic Plains, this poses a very serious seismic risk for the future and has been a major cause of concern in the scientific and emergency management communities. Peninsular India, even though far less active seismically, has also seen some very damaging earthquakes, for instance, the Koyna (1967), Latur (1993) and Bhuj (2001) earthquakes. It is clear that most parts of India are prone to earthquakes of varying magnitudes and with varying probabilities of occurrence.

In the aftermath of these events, the need for a comprehensive database compiling all available data on geological, geophysical and seismological aspects of the entire country was strongly felt, to facilitate seismic hazard assessment, and in 2000, the Seismotectonic Atlas of India and its Environs, was published by the Geological Survey of India (GSI 2000). The Atlas contains 42 maps that cover India and its neighbouring countries without delineating political national boundaries; each map sheet also provides some explanatory notes and illustrative diagrams.

2.2 Ancient and medieval earthquakes

Interest in, and scientific engagement with, earthquakes in India can be traced back three millennia, to ancient Indian texts that contain both quantitative and qualitative understanding on earthquake occurrences, effects and even earthquake magnitude and intensities. These texts also include a number of “theories” on the causes of earthquakes, some of which are rooted in mythological beliefs—such as the notion that earthquakes are caused by the collective “sigh of elephants that are supporting the Earth”—while others have geographical, geological and climatic underpinnings, for example, “earthquakes were caused by the interaction of two strong winds which eventually impacted the oceans and shook the earth” (Iyengar 1999). These ancient texts also classified earthquakes into four categories, according to their direction, time of occurrence and effects: *Agni* (fire); *Vayu* (wind); *Varuna* (water); and *Indra* (rain). And, these ancient texts divided the subcontinent into distinct zones according to the types and effects of earthquakes that occurred there (Iyengar 1999).

Interpretations of archival records of both Persian and Sanskrit origin have referred to several earthquakes in Kashmir and Assam and some in other parts of the country. The first reference to an earthquake in Kashmir is from the Mahabharata (Iyengar et al. 1999); the

Table 1 A brief overview of some significant earthquakes in the Indian subcontinent

Year	Date (local time)	Location	Magnitude and MM/MSK intensity	Remarks
893–894 AD	NA	Near Debal (Sindh), Pakistan	7.5 VIII–X	180,000 reported dead (may be exaggerated), Indus river changed course, Debal town disappeared, affected area similar to that of 1819 and 2001 earthquakes in Kutch
1505	June 6 (~5 AM local time)	Nepal Tibet Border	8.2	Affected a very large region. Caused destruction in western Nepal and Tibet. Monasteries and temples destroyed, tens of thousands of lives lost. Agra (500 km away) was badly affected. Earthquake felt in Delhi
1505	July 6	Kabul	7.3	Numerous houses destroyed in a number of towns, killing many people. Fort badly damaged. Babur, staying at that time outside Kabul, took about a month to repair the Fort
1555	September	Srinagar, Kashmir	7.6	Intensity VII (MSK) in a large area of Kashmir. Massive landslides and rockfalls. Numerous persons killed
1720	July 15	Delhi	7.2 X	Damage to the Fort and to many buildings. Many lives were lost. Cracks developed in ground
1751		Southwest Tibet	7.0	Very large earthquake, consisted of four shocks, buildings collapsed, Temples in Daba district damaged beyond repair
1803	Sept 1 1:30 AM	Garhwal Uttaranchal	7.5	Exact location under debate; some sources mention location near Mathura. Severe damage in the district of Tehri Garhwal, at Gangotri and Badrinath. 200–300 persons killed in Barahat on Bhagirathi river. Complete destruction between Joshimath and Karnaprayag, Liquefaction in Mathura. Qutab minar in Delhi damaged. Dislodged upper turrets of several minarets in Lucknow including that of Imambarah
1819	June 16 11:00 AM	Runn of Kutch	8.0 X	Killed more than 1500 persons; Created an embankment named "Allah Bund" about 100 km long, about 7 to 9 m high; South of Allah Bund, a lake formed when water from ocean rushed into the depression. Felt over radius of 1600 km
1833	August 26 6:00 PM	Bihar–Nepal	7.7 IX	414 persons dead in Nepal, number of deaths in India not known. Affected areas same as that of the 1934 and 1988 Bihar–Nepal earthquakes
1869	January 10 Afternoon	Cachar	7.4	1st earthquake in India where Geological Survey of India carried out an investigation under guidance of their first superintendent, Thomas Oldham

Table 1 continued

Year	Date (local time)	Location	Magnitude and MM/MSK intensity	Remarks
1881	Dec 31 7.30 AM	Car Nicobar region	7.9	Generated tsunamis with a maximum crest height of 0.8 m recorded by eight tide gauges around the Bay of Bengal. Felt over much of India and parts of Burma
1897	June 12 5:11 PM	Assam, India	8.7 XII	About 1500 persons died. Was felt over 4.5 million sq km area, Large scale surface distortion and liquefaction. Stones projected through the air, indicating vertical ground acceleration exceeding 1.0 g
1900	Feb 8 3:11 AM	Coimbatore	6.0 VII	Shock was felt throughout south India. Coimbatore and Coonoor worst affected
1905	April 4 6:20 AM	Kangra	8.0 X	~19,000 persons died. About 10 % population of Kangra and Palanpur tehsils killed. Liquefaction in Bijnor, Hardwar and Roorkee. Considerable damage in Lahore. High intensity around Dehradun and Mussorie (VIII)
1931	August 27 8.30 PM	Mach (Baluchistan)	7.3 VIII	About 120 persons died. Damage to railway establishment led the railway authorities to take up construction of earthquake-resistant quarters for officials
1934	January 15 2:13 PM	Bihar–Nepal	8.3 X	Death toll 7253 in India and 3400 in Nepal; large scale liquefaction in an area of 12,200 sq. km where houses slumped into the ground
1935	May 30 3:02 PM	Quetta	7.7 IX	Caused ~35,000 deaths, largest in any earthquake in the sub-continent in the last two centuries. Population of Quetta was around 60,000 of which about 26,000 persons killed. Administration of the situation became difficult since most civil and police officials were killed in the earthquake. Led to development of seismic codes and systematic reconstruction work by civil, military and railways following earthquake-resistant features
1941	June 26 5.22 PM	Andaman Islands	7.7 VIII	Generated a tsunami ~1.0 m high on the east coast, causing many deaths. Widespread damage to Middle and South Andaman Islands. The Cellular Jail was badly damaged. Earthquake felt in Madras, and in Colombo (Sri Lanka)
1945	Nov 28	Makran Coast, Pakistan	8.0 X	Earthquake accompanied by generation of a tsunami and mud volcanoes. Tsunami reached height of 12 m in some Mekran ports, causing tremendous damage. Tsunami height at Kutch coast 11, and 2 m at Mumbai. About 4000 persons died by earthquake and tsunami. In Mumbai 15 persons were washed away by tsunami

Table 1 continued

Year	Date (local time)	Location	Magnitude and MM/MSK intensity	Remarks
1950	August 15 7:31 PM	Assam–Tibet	8.6 XII	About 1500 persons in India and 2400 in China killed. Caused huge landslides which blocked rivers, and later caused floods as the blockades got cleared. A lot of aftershock activity, with at least one of M7.0
1956	21 July 9:02 PM	Anjar (in Kutch)	6.1 IX	About 115 persons killed; part of Anjar on rocky sites suffered much less damage than the other part
1967	10 December 4:30 AM	Koyna, Maharashtra	6.5 VIII	About 180 persons killed. Caused significant damage to concrete gravity dam. Occurred in area considered non-seismic at the time. An example of reservoir induced earthquake
1970	23 March 8:56 PM	Bharuch	5.2 VII	About 30 persons killed
1988	21 August 4:39 AM	Bihar–Nepal	6.6 IX	Damage pattern same as in 1934 Bihar–Nepal earthquake. About 1000 persons killed
1991	20 October 2:53 AM	Uttarkashi	6.4 IX	768 persons killed. 56 m span Gawana bridge 6 km from Uttarkashi en-route to Gangotri collapsed, causing the pilgrims at Gangotri to be stranded for some time
1993	Sept 30 3:56 AM	Killari (Latur)	6.2 IX	Most deadly earthquake in India since independence with 7928 persons killed. An intra-plate earthquake in a region considered aseismic and placed in lowest seismic zone in the contemporary zone map
1997	22 May 4:22 AM	Jabalpur	6.0 VIII	38 persons killed, about 1000 injured. Several concrete frame buildings with open ground storey suffered structural damage. Numerous masonry buildings suffered damage of staircase mumties
1999	29 March 00:35 AM	Chamoli	6.6 VIII	As a result of 1991 Uttarkashi earthquake, the area had improved constructions from seismic view point. Rather low casualties: about 63 persons died. Some damage to two buildings in Delhi located >200 km away
2001	January 26 8:46 AM	Bhuj (Kutch)	7.7 X	13,805 lives lost. Numerous modern multistory buildings collapsed: including about 130 buildings in Ahmedabad and one in Surat. Showed clearly the vulnerability of modern Indian constructions and the need for seismic code compliance. A number of medium and small earth dams severely damaged
2002	Sept 13 3:58 PM	North Andaman (Diglipur)	6.8 VII	Many poorly constructed buildings damaged

Table 1 continued

Year	Date (local time)	Location	Magnitude and MM/MSK intensity	Remarks
2004	Dec26 6:28 AM	Sumatra	9.4 VII (in Andaman Islands)	Caused most devastating tsunami in history, resulting in ∼250,000 total deaths. In India about 10,000 people died and 5600 people were missing. Damage to structures primarily due to tsunami on mainland India, in Little Andaman and islands to south, damage due primarily to ground shaking
2005	October 8 9:20 AM	Kashmir	7.6 VIII at Uri	Poor performance of masonry buildings was the primary cause of deaths. Unique construction found in this region, dhajji diwari, showed good seismic performance
2011	Sept 28 6:10 PM	Sikkim	6.9 VI	78 deaths in India. Large number of landslides, significant damage to buildings and infrastructure, including RC frame buildings. Sikkim most affected state of India. Nepal, Bhutan, Tibet (China) and Bangladesh sustained damage and losses to varying extent

Mahabharata may have been composed about 2000 years ago (e.g., Singh 2009a). A number of historic earthquakes have been reported from Assam, primarily in the *buranjis* or official records maintained by court officers. These include earthquakes with notable effects, including: the 1556 Gajala earthquake with evidence of what is now known as liquefaction (sand boils, water spouts); the 1697 Sadiya earthquake with an estimated Modified Mercalli Intensity (MMI) of X; and the 1714 earthquake at at Tingkhang and Charaideo Hill with extensive building damage. In addition, according to Iyengar et al. (1999), five different Persian sources describe a destructive earthquake at Agra in 1505 with widespread building collapses, many casualties, and the appearance of ground fissures, as well as an earthquake in Mandaran in West Bengal in 1669, where the appearance of very deep ground fissures suggest an MMI of IX. They also note the Gujarat earthquake of 1705 at Goga with reports of widespread fissures, and the Sirajgunj (in present day Bangladesh) earthquake of 1787 that caused changes in the course of rivers.

Trench investigations in recent times suggest repeated fault activity in the subcontinent and within the Himalayan plate boundary (Wesnousky et al. 1999). Seismo-archaeological evidence also exists in the region corresponding to the Indus Valley Civilization. Excavations at different locations in Kalibangan, an Early and Mature Harappan site, show clear signs of fault rupture and earth movements, implying violent shaking (Kovach et al. 2010). In fact, some archaeologists attribute the end of Early Harappan occupation of Kalibangan to an earthquake. Dholavira, located in the Rann of Kutch in Gujarat, is another Harappan settlement with evidence of earthquake damage and repairs (Kovach et al. 2010). Dholavira is also in the vicinity of two major recent earthquakes, the 1819 M8.0 Kutch earthquake that caused the Allah Bund and the 2001 M7.7 Bhuj earthquake.

2.3 Some significant earthquakes

India's history is full of significant earthquakes that have affected many aspects of Indian life, including population movement, important cultural and religious monuments, local economies as well as construction practices. More than 60 % of the country is in seismic zones with expected shaking of intensity VII and above. The entire Himalayan belt is considered prone to great earthquakes exceeding magnitude 8—in a span of about 50 years four such earthquakes occurred: 1897 Assam (M8.7); 1905 Kangra (M8.0); 1934 Bihar–Nepal (M8.3); and 1950 Assam–Tibet (M8.6). Very severe earthquakes in the Himalayan region are expected that could affect millions in the country, e.g., Bilham et al. (2001).

Table 1 and Fig. 4 provide a brief overview of some of the most significant events, selected considering importance of the event and/or availability of information. For more comprehensive discussion on past earthquakes of the Indian subcontinent, one may refer to Amateur Seismic Centre (2015); Ambraseys and Bilham (2003); Bapat et al. (1983); Oldham (1883); and Quittmeyer and Jacob (1979).

2.4 Seismic risk

Table 1 illustrates how earthquakes in the Indian subcontinent continue to cause unacceptably large number of deaths. The main cause of fatalities in earthquakes in India is collapse of buildings. The number of deaths in an earthquake depends on shaking intensity, vulnerability of the building stock, time and season of the earthquake (whether people will

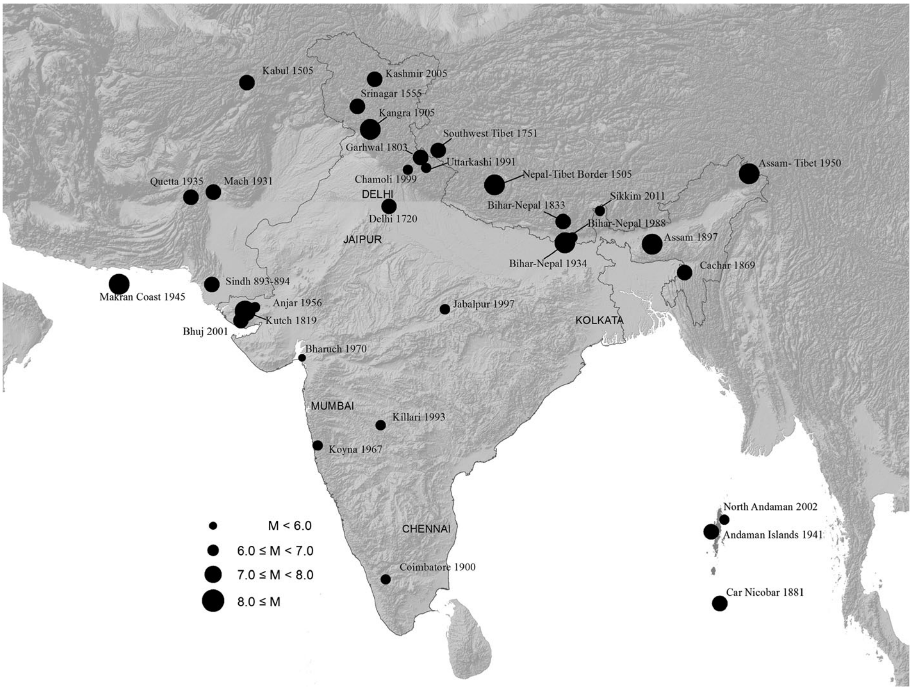


Fig. 4 Location of some significant earthquakes in the Indian subcontinent

be indoors or outdoors at the time of shaking), and to some extent on the efficacy of rescue and relief. Hence, in a theme that will be repeated throughout this monograph, the best protection against earthquake disasters is safer construction.

To illustrate the risk associated with Indian construction, two recent studies on rates of casualties in two earthquakes (Latur 1993; Bhuj 2001) are briefly summarized, as well as a recent study on the vulnerability of modern reinforced concrete buildings in Ahmedabad at the time of the 2001 Bhuj earthquake.

2.4.1 Casualties in two Indian earthquakes

Reliable data on the number of casualties could be obtained for two earthquakes in India, 1993 Latur (M6.2) and 2001 Bhuj (M7.7), from the Government of Maharashtra and the Government of Gujarat, respectively. A total of 7635 persons were killed in 52 villages in the Latur earthquake that occurred early in the morning (3:53 AM local time) on a chilly night (30 September) when most people were sleeping indoors. There were casualties in almost all villages that experienced an intensity of shaking of VII or greater. The earthquake focus was shallow and hence only a small area was affected but with a high level of shaking intensity (up to IX on the MSK scale of intensity). The housing typology was very vulnerable to seismic shaking: random rubble masonry in mud mortar with heavy roofs (Fig. 5). The death toll was quite high, with at least one instance of a village losing one-third of its population during the shaking. The median death rate in the 14 villages sustaining a shaking intensity of IX on the MSK scale was about 20 % of the population, which is an indication of extreme seismic vulnerability.

The 2001 Bhuj earthquake (M7.7), which killed 13,805 persons, occurred at 8:46 AM (local time) when many persons were outdoors. The earthquake affected a very large area, and the intensity of shaking ranged up to X on the MSK scale. The construction types, even though far inferior to what the codes required, were significantly better than those in the Latur region. Further, the timing of earthquake was more favourable in case of Bhuj, since many people were outdoors. Hence, the median death rate was only about 0.2 % of the population for villages that sustained a shaking intensity of IX on the MSK scale. The factor of about 100 in death rates between Latur and Bhuj earthquakes underlines the importance of looking at regional variation in construction typologies in a diverse country

Fig. 5 Collapsed random rubble construction blocks village road in Latur (*courtesy*: NICEE)

such as India. Further, a significant number of modern multi-storey reinforced concrete frame buildings collapsed (Fig. 6) not only in the meizoseismal area of Bhuj earthquake, but also in the city of Ahmedabad.

2.4.2 Ahmedabad buildings and their seismic vulnerability

During the 2001 Bhuj earthquake, Ahmedabad city, located about 230 km from the epicentre, experienced shaking intensity of VII on the MSK scale. The city sustained significant damage to multi-storey reinforced concrete frame buildings that had been built in the previous decade. About 130 such buildings collapsed in Ahmedabad, killing 752 persons. An extensive damage survey was carried out on multi-storey building stock in the city by the Centre for Environmental Planning and Technology (CEPT) (now known as CEPT University). The buildings were classified into different damage categories, ranging from G0 (no damage) to G5 (collapse). Survey results for 2856 such buildings were available and analysed (Singh 2009b) to study vulnerability of RC frame buildings as they existed in Ahmedabad at that time. To benchmark these buildings, a comparison was made with the recommendations of the Applied Technology Council publication, ATC-13, (1985) for RC frame buildings.

ATC-13 defines the ratio of the cost of repairing damage to the replacement value of a facility as the ‘damage factor’ (DF), and provides the means to construct a probability distribution (beta distribution in probabilistic terms) of damage to different facility classes caused by shaking of a given intensity. For instance, Fig. 7 illustrates the probability distribution for mid-rise moment resisting non-ductile RC frame buildings for shaking intensity of VIII. This Fig. implies that if shaking of VIII were to be experienced by this type of building, 33.6 % are expected to undergo damage state 3 (Damage Factor range of 1–10 %), 65.7 % are expected to undergo damage state 4 (DF range 10–30 %), and 0.7 % will undergo damage state 5 (DF range 30–60 %).

The damage data for RC frame buildings in Ahmedabad due to shaking intensity VII caused by the 2001 earthquake came closest to ATC-13 data for intensity VIII for non-ductile RC frame buildings in terms of estimating the average damage factor. Hence,

Fig. 6 Apartment collapse in 2001 Bhuj earthquake (photo: C. V. R. Murty)

Fig. 7 Probability distribution of damage to mid-rise moment resisting non-ductile frame at MMI VIII as per ATC-13 (1985)

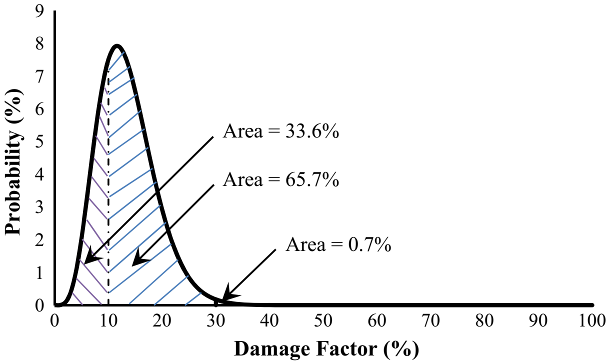
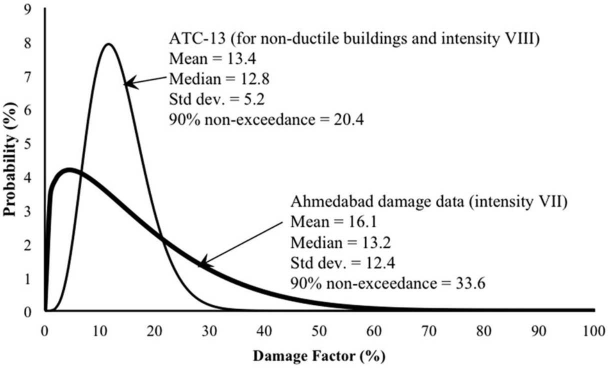


Fig. 8 Comparison of probability distribution of damage in 2001 earthquake in Ahmedabad



Ahmedabad buildings in 2001 were clearly of a very low quality in terms of design and construction. Figure 8 shows the probability distribution for the Ahmedabad buildings (intensity VII during 2001 earthquake) and that for intensity VIII for non-ductile buildings as per ATC-13. While the mean and the median values of damage factor are quite comparable, the standard deviation and damage factor for the 90 % non-exceedance probability are significantly higher for Ahmedabad buildings as compared to ATC-13 data. This implies that even with using an increased shaking intensity of one level, the number of severely damaged and collapsed buildings (and hence the casualties) for Ahmedabad buildings will be significantly higher that what is estimated by the ATC-13 method.

The study (Singh 2009b) clearly illustrates the high vulnerability of RC frame buildings that were built in Ahmedabad prior to the 2001 earthquake; this was also obvious from the unacceptably high number of collapses and deaths. The quality of construction in Ahmedabad has since improved somewhat after the earthquake but is still not comparable to that in the developed countries.

2.5 Some observations

Clearly, a large part of India is prone to strong earthquake-induced shaking, and with highly vulnerable constructions, there is huge risk of death and destruction. Areas in seismic zones IV and V of the Indian zone map encompass some of the most populated regions of India, including Delhi, the world's second most populous city. In addition to being so highly populated, Delhi is projected to grow from 25 million to 36 million by 2030, thus even further increasing its vulnerability (United Nations 2014).

Some of the construction typologies prevalent in India are particularly vulnerable to earthquake shaking. In 1994, the Government of India constituted an Expert Group to study the impact of natural hazards on housing and infrastructure in the country and to identify areas vulnerable to the damaging effects of hazards such as earthquakes, cyclones, floods, etc., prepare a vulnerability atlas delineating the vulnerable areas along with the risk levels of the housing stock in those areas and formulate a strategy for setting up the techno-legal regime for the enforcement of disaster resistant construction practices in settlements in hazard prone areas. Based on the Expert Group report, the Building Materials & Technology Promotion Council (BMTPC) published the Vulnerability Atlas of India in 1997. The Atlas considered housing typologies based on the 1991 Census data on housing. The data did not include any physical or structural characteristics of the houses based on building elements such as walls, roofs and floors, an omission that was addressed in the 2001 Census.

The 2011 Census of India indicates that there are over 330 million housing units in the country (GoI 2011a). Two-thirds of these are rural houses and almost 30 % are in earthquake zones IV and V (BMTPC 2006). Eighty-five percent of these houses are made with mud and un-burnt brick, burnt brick or stone walls, all of which can be quite vulnerable if not constructed and maintained properly (BMTPC 2006). Even with a huge percentage of the housing stock in rural areas, India has a rapidly growing urban population. In 2001, about 286 million people were living in urban areas across India, the second largest urban population in the world. The Census of India (2011) shows the urban population had increased to 377 million, thereby registering a growth of around 32 %. As per recent estimates, nearly 590 million people will live in Indian cities by 2030 (Make India 2015). According to the Government of India Ministry of Housing and Urban Poverty Alleviation (GoI 2012), 18.78 million households are facing a housing shortage in urban India, while the housing shortage in rural areas is 40 million (GoI 2011b). In his Budget Speech (GOI 2015; The Hindu 2015), the Finance Minister announced Housing for All by 2022, and further, every house in India should have access to basic facilities of 24-h power supply, clean drinking water, a toilet, and be connected to a road. This shows that despite having a huge problem of unsafe buildings that currently exist, we will also be constructing a huge number of new buildings. Hence, there is a tremendous urgency to ensure that new constructions are equipped with not only the basic facilities but should also be safe.

3 Early developments in earthquake science and engineering

3.1 Earthquake science

Damaging earthquakes in India have been studied systematically for about two centuries. The Kutch earthquake of 1819 (M8.0) was well documented by Macmurdo in the 1824 issue of The Philosophical Magazine (Macmurdo 1824). The earthquake caused a 100 km long and 3 m high fault scarp that was named Allah Bund (embankment created by God). This earthquake provided the "earliest well documented instance of faulting during an earthquake" (Richter 1958). Another important discovery out of this earthquake was what is now commonly termed as "site effects". It was clearly noted that buildings on rock sites performed much better than those on the alluvium. Lt Baird Smith studied several early earthquakes in India and wrote articles about them in the Journal of the Asiatic Society of Bengal (Baird-Smith 1843).

3.1.1 Assam earthquake

A more systematic study of earthquakes in India was started by Thomas Oldham, the first Superintendent of the Geological Survey of India (GSI). He carried out a study of the Cachar earthquake of 1869 and compiled the first catalogue of earthquakes in India; both these were completed later by his son R. D. Oldham who succeeded him as Superintendent of GSI. The study on the Cachar earthquake was published in the memoirs of the Geological Survey of India as well as Science (Davis 1883). The earthquake was felt over an area of 250,000 square miles, and a considerable amount of liquefaction was reported.

By the time of the 1897 Assam earthquake (M8.7), R. D. Oldham must have already had considerable experience and knowledge of earthquakes as a consequence of working on completing his father's work. As a result, he was able to undertake a scientific and very comprehensive study of that earthquake, and the resulting 400 page publication Memoir of the Geological Survey of India in 1899 is considered the first comprehensive scientific study of an earthquake anywhere in the world, e.g., "one of the most valuable source books in seismology" (Richter 1958).

The 1897 Assam earthquake is considered to be one of the greatest earthquakes to have occurred anywhere. It was felt over a very large area, as far west as Nagpur in Central India and caused severe damage in a radius of 500 km. For instance, extensive building damages were reported in Calcutta, 470 km from the epicentre. Higher shaking intensities were seen in the Ganges and Brahmaputra river basins, as expected at the river basin sites with soft sediments, due to amplification (Fig. 9). The earthquake was associated with intense aftershock activity that continued for almost 10 years. A hanging lamp continued to swing continuously for three or 4 days as a result of aftershocks (Oldham 1899) (Fig. 10).

The earthquake caused a number of surface ruptures, including the Chedrang fault on which a vertical slip of about 11 meters took place over a length of 19 km. Large-scale surface distortions and land-surface deformations took place, causing an interruption of the drainage channels. In addition, largescale liquefaction occurred, and river banks slumped into the main channels. Railway systems were damaged extensively: rails were bent on a large scale, bridge piers moved laterally and bridge spans shortened (Fig. 11). The descriptions of the 1897 Assam earthquake by Oldham provided the principal model for the highest grade, XII, of the MMI Scale (Richter 1958).

Mallet's seismometers consisting of cylinders of various diameters were set up in 1882 in Shillong and Silchar. Each seismometer comprised a set of nine cylinders 12 inches (305 mm) in height and diameters ranging from 1 inch (25 mm) to 9 inch (229 mm). During the main shock of the 1897 Assam earthquake, the whole series of cylinders was overthrown north-eastwards. The minimum acceleration and velocity corresponding to overthrow of the largest cylinder has been estimated as 0.74 g and 0.61 m/s, respectively (Oldham 1899; Manchester Geographical Society 2013). At Silchar (about 200 km from Shillong), the cylinders of 1.0 inch (25 mm) and 1.5 inch (38 mm) were overthrown which corresponds to a minimum acceleration of 0.12 g (Oldham 1899).

Based on a careful recording and a study of the overthrow of stones in the earthquake, Oldham concluded that the vertical acceleration in the meizoseismal region must have exceeded that of gravity (1.0 g). Oldham studied seismographic recordings of the Assam

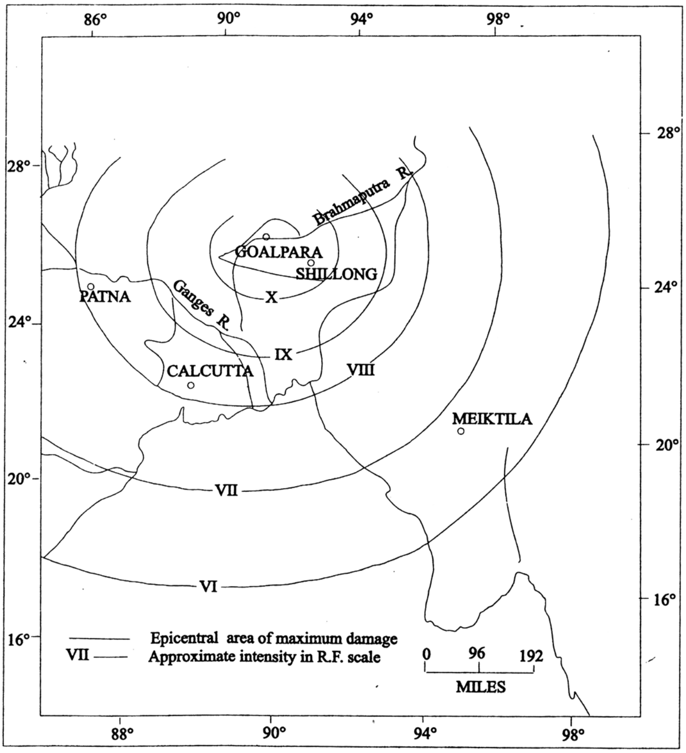


Fig. 9 Isoseismal Map of Assam Earthquake of June 12, 1897 (GSI 2000)

earthquake and it revealed for the first time the existence of longitudinal (P), transverse (S) and surface (L) waves.

3.1.2 Bihar–Nepal earthquakes

Another interesting earthquake in India that contributed significantly to the development of seismology is the Bihar–Nepal earthquake of January 15, 1934. The earthquake lasted up to 5 min and was felt up to 1600 km from the epicentre, resulting in 7253 deaths in India and 3400 in Nepal. An area of about 130 km long and about 30 km wide experienced shaking intensity of X (on the I to X Mercalli scale). The isoseismals indicate lower observed intensities to the east and south east of the epicentral area, while these are stronger along the Ganges Basin, due to amplification of seismic waves (Fig. 12). The death toll was low, considering the violence of the earthquake, because (a) most people were awake and outdoors in the afternoon (2.15 PM), and (b) the most violent shaking occurred more than 2 min after the earthquake began and hence those indoors were able to rush outdoors. Besides the epicentral area, Munger to the south and Kathmandu valley to the north, both located about 160 km away from the epicentre, also sustained shaking of intensity X due to the peculiar geological setting of these two locations. Munger lies at the junction of alluvium and Peninsula rocks; at such junctions the alluvium is known to experience much stronger shaking. Munger also showed clear evidence of buildings located on rock outcrops suffering much lower damage than those on the alluvium. The

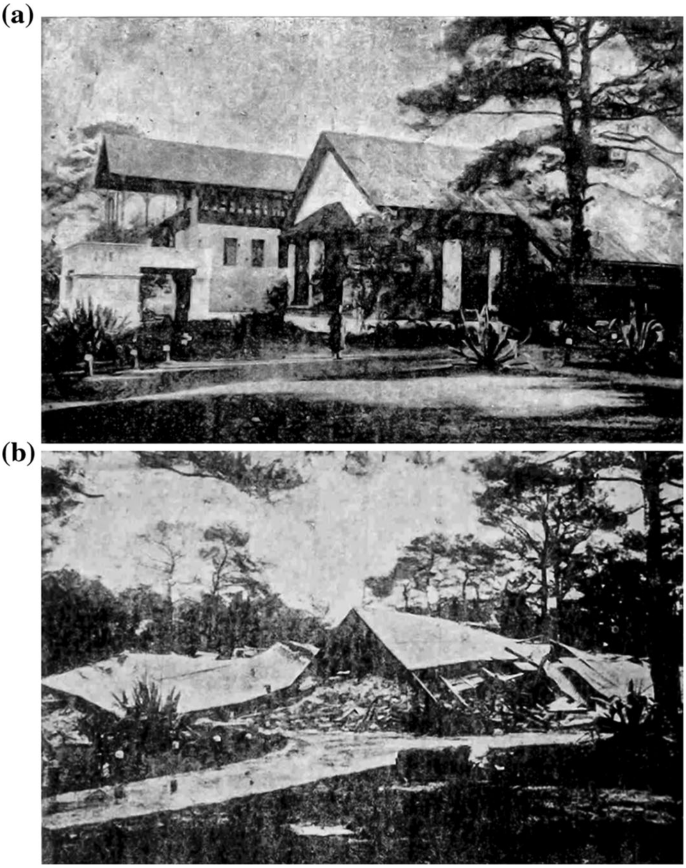


Fig. 10 The Government House in Shillong **a** before and **b** after the 1897 earthquake (Oldham 1899)

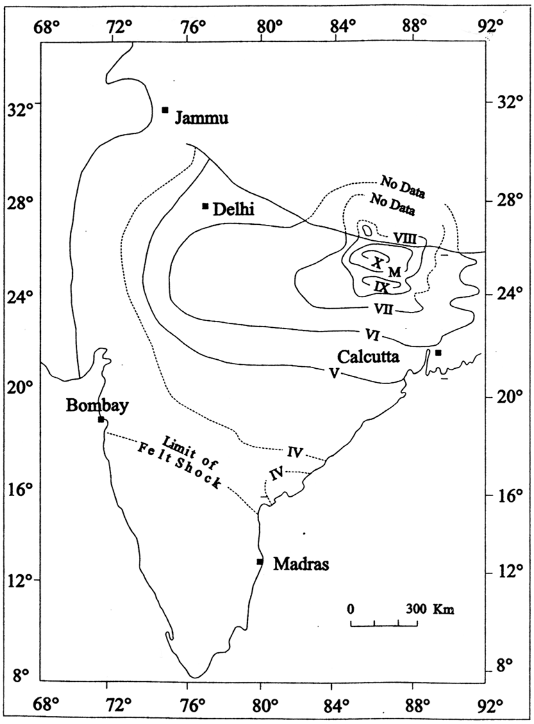
Kathmandu valley consists of unconsolidated sediments and hence the ground motion was amplified.

Interestingly, the damage pattern in the 1934 earthquake was similar to what had earlier been recorded for the 1833 earthquake in the region that killed 414 persons in Nepal and an unknown number in India. The memoirs of the GSI (1939) on the 1934 earthquake quote Lt. Baird-Smith (1843) as saying “It is a remarkable fact, that Monghyr seems to suffer more from earthquake shocks, from whatever direction these may come, than any other place in its vicinity. This was observed during the shock from the lateral Himalayan tract, of the 26th August 1833, again during that of the 11th November 1842, and I would say from the information before me, that on the present occasion, the shocks were smarter at Monghyr than at any other spot.” The 1988 (M 6.6) earthquake in northern Bihar again showed the same pattern of high seismic shaking intensity in the epicentral area, Munger, and Kathmandu valley.

Large scale liquefaction was caused by the 1934 earthquake. Buildings slumped into the ground and tilted in a large area ($\sim$300 km length and width of 65 km) that was termed a “slump belt”. Massive subsidence of road and railway embankments took place, and lakes and other depressions became shallower.

Fig. 11 Damaged railway bridge in Assam 1897 earthquake (Oldham 1899)

Fig. 12 Isoseismal Map of the Earthquake of January 15, 1934 (GSI 2000)



Based on a study of fallen objects, an acceleration of 0.33 g was estimated at Munger and 0.20–0.30 g in areas of intensity IX; such estimates tend to be lower-bound estimates since an object would have likely fallen with a higher acceleration. The first seismograph in India was installed in 1898 at the Bombay Observatory (Jain and Nigam 2000). S. C. Roy, Director of the Meteorological Department in Burma, contributed a chapter on seismology in the GSI report of the 1934 Bihar–Nepal earthquake (GSI 1939). He interpreted the seismic waves and located the earthquake epicentre from their arrival times. Roy was also one of the first to count the frequency rate of aftershocks using records at a seismograph station. Because the number fell from 200 to 16 in a month he concluded that the crustal strain had been relieved completely (Jain 2008).

3.2 Earthquake engineering

At the same time that advances were being made in earthquake science after these significant earthquakes, there were also advances in engineering and construction practices. There were several indigenous construction typologies that showed excellent performance in strong earthquake shaking. These typologies were developed much before the formal emergence of earthquake engineering, and highlight the fact that a lot of earthquake safety can be achieved through the use of common sense, provided there is commitment to do so. Assam-type houses (prevalent in the northeastern states) and timber houses in the Andaman and Nicobar islands have consistently shown good seismic performance. Unfortunately, these building typologies have been abandoned in these highly vulnerable regions due to (a) fire hazard in timber buildings, (b) environmental concerns regarding use of timber, and (c) due to the mistaken belief that reinforced concrete or masonry buildings will be safer even when adequate quality control cannot be ensured (Jain 2006).

3.2.1 Dhajji Diwari and Taq

Dhajji Diwari and Taq type constructions are common in Kashmir and in Himachal Pradesh, areas that have experienced strong earthquakes in the past and that are placed in the highest seismic zone in the Indian code. The fact that Dhajji Diwari is a common sight in Srinagar (Kashmir) but can hardly be seen 120 km away at Muzaffarabad (in Pakistan-occupied Kashmir) indicates that this may have developed as a result of a damaging earthquake in Srinagar in the last couple of centuries.

Dhajji Diwari (patch quilt wall) consists of burnt clay brick masonry placed inside a timber frame, so as to create a patchwork of small-size masonry panels that are confined by timber members (Fig. 13). Due to confinement provided by timber elements, the diagonal shear cracks do not propagate from one panel to the other, and the possibility of out-of-plane collapse of masonry panels is reduced considerably. As shown in Fig. 14, in some instances, lower floors may consist of stone masonry, while the upper storey and gable portion of the wall are built with the Dhajji Diwari technique (Hicyilmaz et al. 2010).

In *Taq* construction, large wood pieces are used as horizontal runners embedded in the heavy masonry walls (Fig. 15). This improves the lateral load resistance of the building as shown by its earthquake performance historically (Rai and Murty 2006).

Fig. 13 Traditional Dhajji Dewari construction in Srinagar (photo: author)

Fig. 14 Traditional construction is visible in this hospital in Kashmir, with upper storey of Dhajji Dewari and lower storey of masonry (photo: author)

3.2.2 Assam type house

As noted, the 1897 Assam earthquake caused widespread and serious damage over an area of about 500 km radius. In and around Shillong, all the stone buildings were leveled, about half of the "*ekra*-type" buildings (wooden frame work with walls of san grass covered in plaster) collapsed due to heavy stone chimneys, while the plank buildings constructed on the "log hut" principle did well. As a result of this earthquake, a new building typology was developed that is commonly known as "Assam Type" housing (Fig. 16).

The typical Assam Type house is a single or two storey structure with brick or stone masonry up to the plinth level and mud plastered *ekra* panels braced by either timber or bamboo horizontal, vertical and at times, diagonal, confining members. *Ekra* is a kind of

Fig. 15 Typical *taq* construction in Kashmir, with horizontal timber runners (photo: author)

Fig. 16 Typical Assam-type house in Gangkok (photo: A. Sheth)

reed that grows on the banks of the Brahmaputra river and is used in combination with mud to form flexible and lightweight wall panels that are able to accommodate deformation during earthquake shaking, but do not collapse like brittle brick masonry infill walls. Sloping roofs consist of metal sheets or a thick stack of *ekra* panels over a timber or steel truss. Gable end walls have additional bracing above the eaves level to protect the upper ends of the walls.

This type of building became prevalent in the entire north-eastern part of India, and over the years has shown excellent seismic performance. Unfortunately, as noted above, in recent decades these buildings are being phased out because of concerns over the fire hazard, to minimize the use of timber and because of increasing interest in RC frame construction.

3.2.3 Earthquake reconstruction in Baluchistan

In the 1930s, some fascinating developments took place in Quetta (Baluchistan; now in Pakistan) in earthquake-resistant construction, development of codes and implementation of the same. Considering that these developments took place in a relatively isolated place, at a time when communication systems were not developed, and led by persons who were themselves new to the problem of earthquakes is inspirational in the context of the contemporary situation for seismic safety in many parts of the world.

On August 27, 1931, an M 7.3 earthquake in Mach, located about 60 km from Quetta, killed about 100 persons; the maximum shaking intensity was VIII on Rossi-Forrel (RF) scale. Upon seeing the poor performance of buildings there, the railways instructed a young engineer in his twenties, Sardari Lal Kumar to design earthquake-resistant quarters for railway staff in Quetta. In a very interesting paper presented in 1933 in the Punjab Engineering Congress, Kumar described his understanding of the concept of earthquake-resistant construction, and provided details of his project (Kumar 1933). The paper also contains the first ever seismic zone map for India (Fig. 17) and his recommendations on seismic design coefficients for the different zones (Table 2). In fact, the proceedings of the

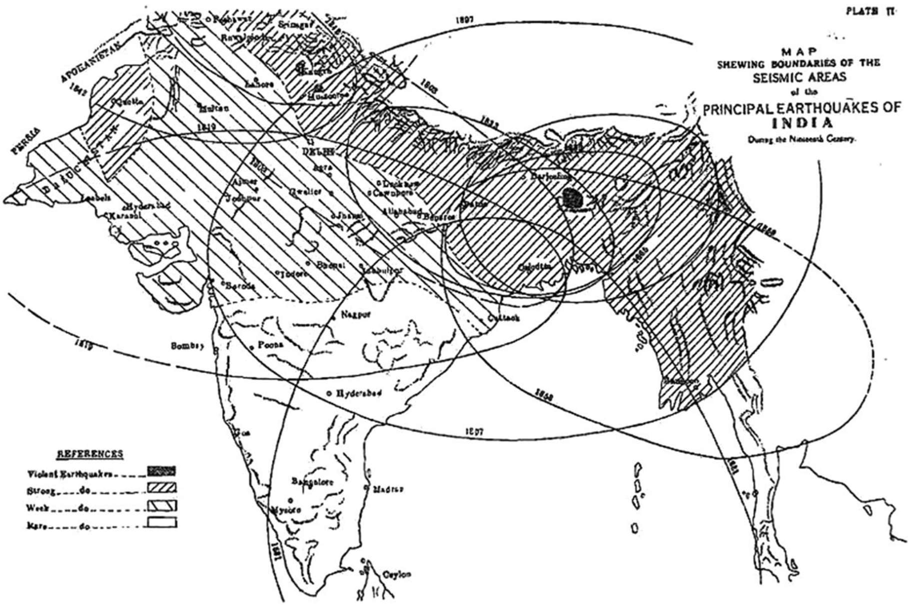


Fig. 17 First seismic zone map of India (Kumar 1933)

Table 2 Seismic factors for different seismic zones suggested by Kumar (1933)

Class of building	Values of the seismic factor			
	Areas of violent earthquakes	Areas of strong earthquakes	Areas of weak earthquakes	Areas of rare earthquakes
A	0.15 g	0.10 g	0.05 g	Nil
B	0.10 g	0.075 g	Nil	Nil

Type A monumental buildings and those more than 50 ft. high, *Type B* all others

meeting also included interesting questions that were asked of Kumar by his seniors after his presentation and the answers he provided to those.

On May 31, 1935, Quetta experienced one of the most deadly earthquakes (M7.7; intensity up to IX on RF scale). The number of deaths was reported in the range of 20,000–30,000, which amounts to about one-half of the population of Quetta at that time. Interestingly enough, the only houses that withstood the earthquake shaking were the railway quarters that had been constructed by the railways as earthquake-resistant (Fig. 18). These must have proved to be an excellent testament to the local population and the administration, and had a deep impact on the massive reconstruction that took place in the town.

The reconstruction programme involved three main agencies: the railways, the military, and the civil administration, and all three were quite diligent about earthquake resistance for the new constructions (Thomson 1940; GoI 1940; Robertson 1948). A seismic coefficient of 0.125 was adopted and comprehensive guidelines developed for earthquake-resistant features. A code was also proposed along with an excellent commentary (GoI 1940). These constructions performed extremely well in the 1941 earthquake (RF intensity VIII to IX) (Mair 1942).

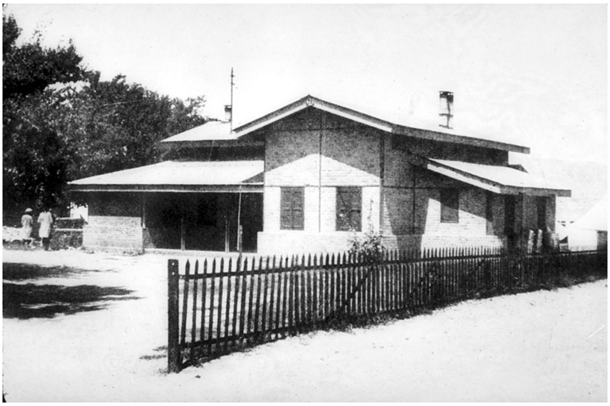


Fig. 18 A railway bungalow built after 1931 earthquake of vertical and horizontal iron rails with brick panels. The few buildings of this type (including one under construction) escaped damage in 1935, though surrounding buildings of unreinforced brick were destroyed (photo: W. D. West, *source*: NISEE–PEER University of California Berkeley)

The entire series of episodes in Quetta in the 1930's was rather unique not just for India but perhaps anywhere in the world: (a) a damaging earthquake inspires an organization (railways) to build a few earthquake-resistant houses, and notwithstanding that the persons at the helm did not have any knowledge about earthquakes, they learn about earthquake safety, build those houses, document their learning, (b) within a few years, performance of these houses in a major earthquake demonstrates that it is possible to build safe houses and inspires the entire reconstruction programme to focus on safety, (c) reconstruction itself is carried out with a complete focus upon safety and a number of construction innovations result, and (d) finally, yet another earthquake within a few years shows that the reconstruction programme had successfully achieved safety. For the first time, seismic codes were developed and implemented in the subcontinent. In order to introduce reinforcement in the masonry walls, a new type of masonry bond (Quetta Bond) was developed. The concept of providing reinforced concrete bands at plinth, lintel, and roof levels in masonry buildings evolved.

Another devastating earthquake took place in 1934 in a part of India (Bihar) that was far more densely populated, that was far better connected, and that had perhaps far better intellectual and engineering resources available. A detailed report on the 1934 Bihar–Nepal earthquake published by the Geological Survey of India in 1939 (GSI 1939) has the following statement regarding Quetta:

> In the Quetta area an excellent building code has recently been drawn up, and reconstruction has been rigidly enforced in terms of that code. Such enforcement is, perhaps, easier in such a military area, but at least Quetta provides an example of the practicability of a building code and of its usefulness. It is, perhaps, not too much to hope that the rest of Northern India will some day follow Quetta's lead.

3.2.4 Seismic retrofitting in Andaman Islands in the 1940s

During a reconnaissance field visit to Port Blair 2 weeks after the December 26, 2004 earthquake and tsunami, the author was surprised to discover some excellent examples of retrofitting, including in the largest mosque of the Andaman and Nicobar (A&N) islands at Port Blair known as *Jama Masjid,* located in the Aberdeen area. The mosque, made of brick masonry with arches, domes and minarets, was completed in 1913; its plan is about 75 feet by 106 feet, and height is 66 feet. A number of tie rods across the halls tie the walls together and ensure that these walls act together in the event of ground shaking, and thus prevent collapse. While there were many examples of new RC frame buildings in Port Blair that were damaged in the 2004 earthquake, this building responded very well, with only a small collapse of one of its minor minarets. Mr Yameen Mohammed Murtaza, an electrical engineer working for the Electricity Department in the A&N Islands, proudly mentioned that his grandfather, an Overseer in the local Public Works Department, was instrumental in putting the tie rods in after the mosque was damaged in the earthquake of 1941. In about 2002 the mosque was being renovated and, since by then many of the tie rods had fallen due to corrosion, Mr. Murtaza decided to repair the tie rods, perhaps as a mark of respect for his grandfather's efforts in the forties (Fig. 19).

The retrofitting of the mosque was rather intriguing to the author. The local engineers in the A&N islands in the forties understood how best to safeguard a masonry building from earthquakes. He expected to see something more interesting after that, but where?

In 1858, the British established a high security penal colony at Port Blair, and occupied neighbouring Ross Island for their offices and residences (Fig. 20). In 1942, about

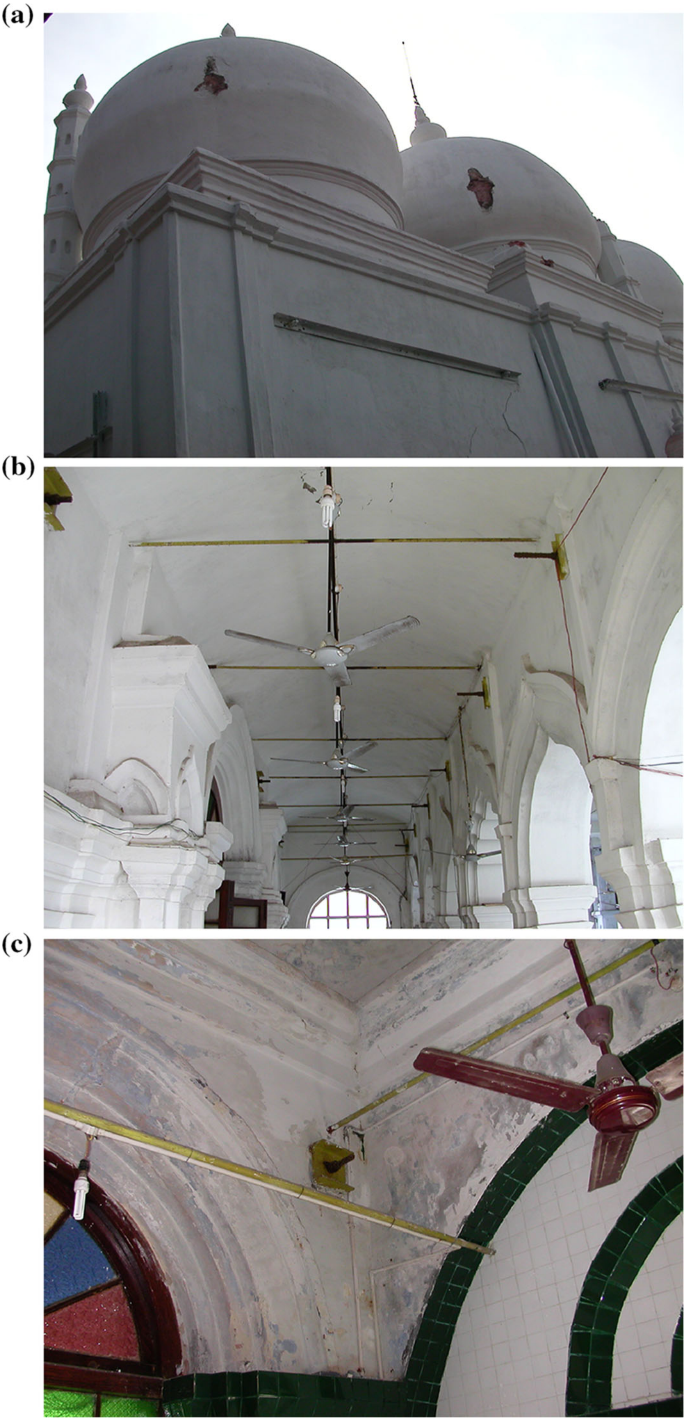


Fig. 19 Jama Masjid in Port Blair **a** Notice the iron angle for anchoring the tie rods used for retrofitting **b** Tie rods used for retrofitting **c** Tie-rods placed in both directions (photos: author)

Fig. 20 Historic photo showing dock and original structures on Ross Island (photo: author)

9 months after the earthquake, the Japanese took over the islands and occupied Ross Island until 1945 when the Japanese forces surrendered to the British and Indian troops. Ross Island has remained abandoned ever since. Only a few years ago it was turned into a day destination for tourists maintained and managed by the Indian Navy. Post-tsunami there were no tourists and hence, Ross Island was closed for visits. However, friendly officers of the Indian Navy assisted the author with a visit to the Island, where a treat awaited in terms of historical seismic retrofitting.

Most of the buildings on the Island are made of brick masonry and have either collapsed or are in ruins (Fig. 21). Some have huge *Peepul* trees growing on them! But upon examination, the author found that each of these buildings had been seismically retrofitted with the use of tie rods. It took him a while to locate the tie rods in the ruins of the Church, but clearly the Church was not left out of the retrofitting plans (Fig. 22).

The arches too were provided with tie rods, so that in the case of shaking the tie rods would take the tension forces generated and save the arches from collapse (since masonry arches transfer the vertical loads through compression, and are not effective in carrying tension generated during ground shaking).

The above examples show that it was possible to carry out earthquake-resistant design and retrofitting before the formal evolution of earthquake engineering discipline and this should be a source of inspiration to our current generation of engineers and architects. We have much to learn from a careful study of historic practices.

4 Post independence developments

As discussed earlier, the first systematic developments in earthquake-resistant construction took place in Quetta in the thirties. However, this remained a one-time local effort driven by unique circumstances and coincidences. The more formal institutionalization of earthquake engineering in India happened in the late 1950's and the 1960's (Jain 2008). In that sense, India was amongst the few countries that started formal earthquake engineering efforts rather early.

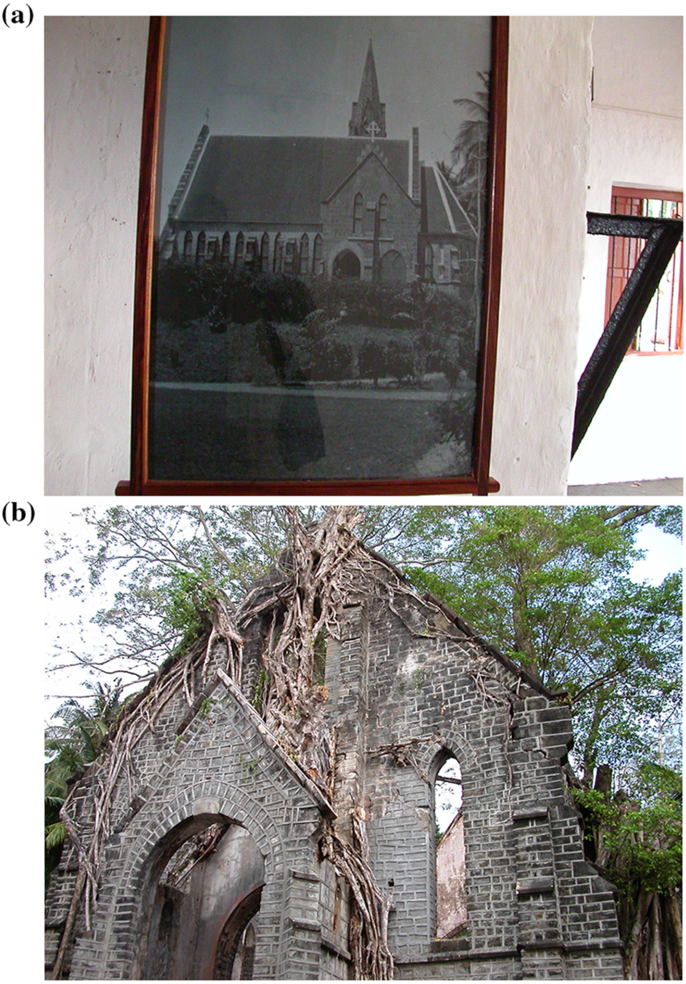


Fig. 21 **a** Photo of Church when built **b** Church as its stands today (photos: author)

A great deal of credit for institutionalization of earthquake engineering in India can be given to the vision and leadership of A. N. Khosla, an eminent hydraulic engineer. After studying civil engineering at Thomason College in Roorkee (now IIT Roorkee), Khosla joined the Irrigation Branch of the Public Works Department. He had a very distinguished career as an engineer, made some pioneering innovations in engineering, and was involved in numerous river valley projects, including the Bhakra dam. In the case of Bhakra, he was engaged at various stages during most of his engineering career: starting with surveys and investigations during 1917–1921, to serving as vice-chairman and later as chairman of the board of consultants for the dam, until it was commissioned in 1963. Bhakra is one of the tallest gravity dams in the world, the tallest in India, and is located in a highly seismic area that is not too far from the site of the magnitude 8.0 Kangra earthquake of 1905. Khosla later held other important engineering responsibilities such as the Chairman of the Central Waterways, Irrigation and Navigation Commission (now, Central Water Commission)

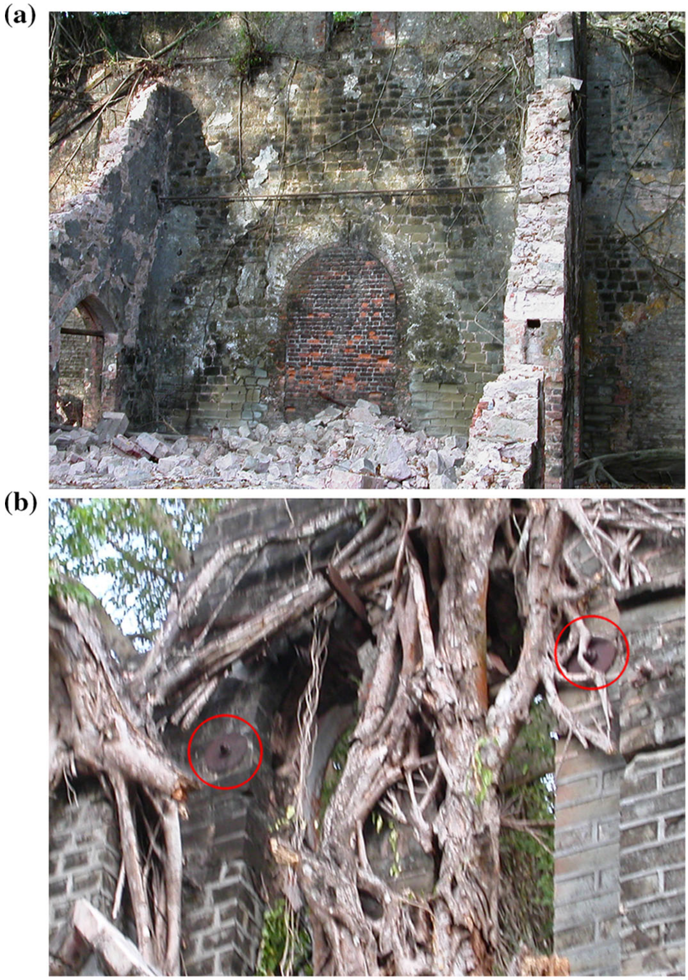


Fig. 22 **a** Tie rods visible in church ruins as well as **b** Anchor bolts visible (photos: author)

during 1945–1953, Vice Chancellor of the University of Roorkee during 1954–1959, as Member of the Planning Commission of India during 1959–1962 and Governor of Orissa during 1962–1968 (Parthasarathy 2003) (Fig. 23).

With his various responsibilities in major engineering projects, Khosla could have been very concerned with the need to design and construct structures that can withstand earthquakes. As Chairman of the Central Board of Geophysics, in a preface to proceedings of a seminar on the Great Assam–Tibet earthquake of 1950 (M8.7), Khosla wrote: "The seismological work in India has not so far received adequate attention and when compared with Japan, USA and some other countries, it is lagging far behind……the science of geophysics, although a newcomer in the field, has vital bearing on many aspects of our development plans, engineering, industrial and agricultural" (Rao 1953).

As Vice Chancellor of the University of Roorkee, Khosla happened to visit the California Institute of Technology (Caltech) in the USA in 1957 and was intrigued by the

Fig. 23 A. N. Khosla, visionary who was instrumental in institutionalizing earthquake engineering in India (Mital 2008)

earthquake engineering being pursued there. He worked out an arrangement with Caltech to seek their help in establishing earthquake engineering at Roorkee, best described in the words of Prof Donald Hudson of Caltech (Hudson, interviewed by Cohen 1997):

> Khosla came to Caltech and spent a couple of weeks. This was in the late 1950s. He was very interested in what we were doing. He was interested in earthquake work. He was also much interested in dynamics laboratory. I had set up a little laboratory for dynamic measurements of all kinds. He spent quite a little time looking over what we were doing. Finally he came in 1 day and said, "I'm very interested in what you're doing. I'd like to do the same things in my school. So I've arranged with Dr. DuBridge [Caltech president Lee A. DuBridge] that you should take a leave of absence and come over to India for a while." …. So the arrangement was that he would send over his best man to work with me for 6 months. We would plan the laboratory here, order all new equipment, and get everything packed up and ready to ship to Roorkee. And then I would come to Roorkee and spend six months or so. Then he would send two more of his best people to Caltech for a year.

As a result, Professor Jai Krishna, a faculty member at Roorkee in structural engineering, spent several months at Caltech to learn earthquake engineering and on his return Professors D. E. Hudson and G. W. Housner of Caltech visited Roorkee for about 6 months and 6 weeks, respectively. With their help, Roorkee started to teach earthquake engineering, developed a laboratory and started a research programme (Fig. 24).

Khosla had a very good rapport with the then Prime Minister Nehru who visited Bhakra Dam a number of times, and this was of great value to developing earthquake engineering at Roorkee. For instance, Hudson in his oral history mentions: "And, sure enough, they got him [Nehru] to come and inspect our school. We showed him the lab and everything we were doing [in earthquake engineering at Roorkee]. He was very interested. So, from then on, we got the full backing from the government of India. Without that, of course, we could have done nothing. That was, again, just kind of fortuitous—when personal connections were involved from way back" (Hudson, interviewed by S. Cohen 1997).

During his stay at Roorkee, Hudson also helped develop "structural response recorders" (SRR) (Cloud and Hudson 1961; Krishna and Chandrasekaran 1965) which consist of six seismoscopes (of natural periods 0.40, 0.75 and 1.25 s; damping 5 and 10 %) (Fig. 25). A

Fig. 24 President of India Fakhruddin Ali Ahmad visits Roorkee in 1976. Jai Krishna in profile to centre right explaining the model tests for masonry houses (Mital 2008)

Fig. 25 Arrangement of a typical structural response recorder (photo: A. Mathur)

seismoscope provides maximum response regardless of the direction of motion within the horizontal plane (Fig. 25) of an oscillator during an earthquake without providing the time history as shown in Fig. 26. Hence, the SRR was designed to provide three points on 5 % damping response spectrum and three points on 10 % damping response spectrum. Several hundred such instruments were installed all over the country by the Earthquake Engineering Department of Roorkee under the Indian National Strong Motion Instrumentation Network (INSMIN) programme. The SRRs, besides being very inexpensive (as compared to more modern Strong Motion Accelerographs, SMAs) required no power supply and hardly any maintenance. As a result, these have been very valuable sources of information in some of the past earthquakes in India, particularly in instances where records from more modern instruments could not be obtained. It has been shown that notwithstanding the simplicity of such instruments, the reliability of responses obtained from them are comparable to the responses obtained from SMAs (Jain et al. 2012).

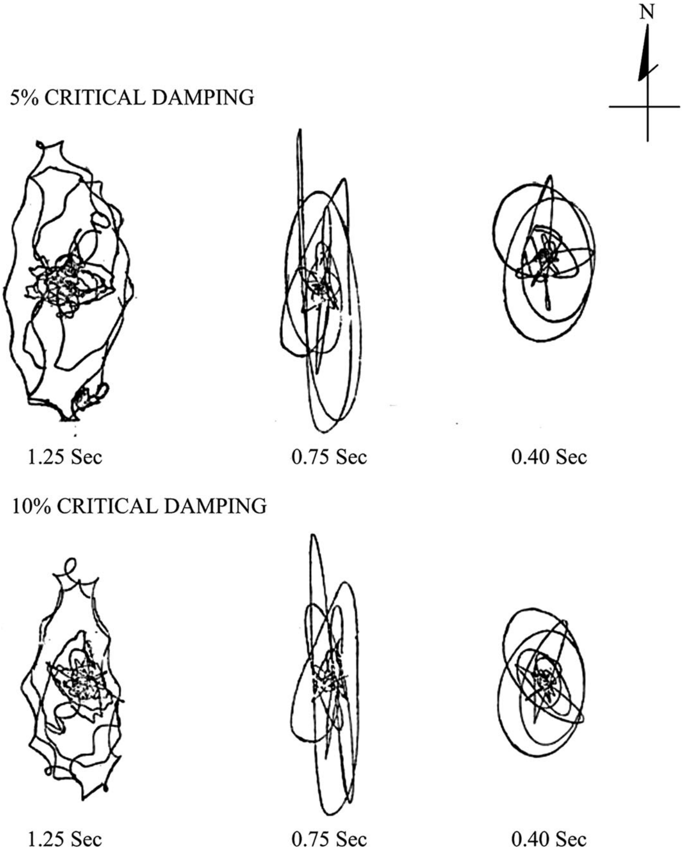


Fig. 26 Typical structural response record (University of Roorkee 1988)

Hudson and Housner also helped Jai Krishna to organize the first ever earthquake engineering conference in India, the first “Symposium on Earthquake Engineering” in 1959. The School for Research and Training in Earthquake Engineering (SRTEE) was established at Roorkee in 1960, which later became the Department of Earthquake Engineering. Under Jai Krishna’s leadership, the first national seismic code (IS 1893) was published by Indian Standards Institute (now, Bureau of Indian Standards) in 1962. He also formed the Indian Society of Earthquake Technology in 1962.

As per the original plan of Khosla’s, two young faculty members of Roorkee, A. R. Chandrasekaran and L. S. Srivastava were sent to Caltech to learn earthquake engineering for 1 year each, after the visit of Hudson and Housner. Both contributed to earthquake engineering in India for many years upon their return. The entire plan was a very fine example of capacity-building in a new disciplinary area for a developing country and could form an excellent model even for twenty-first century India.

Clearly, great work was done in the late fifties and the early sixties on institutional developments towards earthquake engineering. The following quote from Hudson in his oral history describes how far advanced Roorkee was in the mid-sixties: “… One of the new buildings was a big earthquake laboratory—Earthquake Engineering Laboratory.

They had much better facilities there than we ever had here. This was all due to the man that they sent over to work with me, Dr. Jai Krishna, who turned out to be extremely able. He became vice chancellor of the university, and then president of the International Association for Earthquake Engineering ….''(Hudson, interviewed by S. Cohen 1997).

The 1967 Koyna earthquake (M6.7) occurred in an area considered non-seismic at that time. It killed about 200 persons and caused structural damage to Koyna Dam. The earthquake provided much needed articulation for incorporation of earthquake engineering design in major projects in India and provided a tremendous opportunity to the Earthquake School at Roorkee to contribute to numerous projects such as nuclear power plants, dams, and bridges. In his Caltech oral history, Housner states: "the fellows—Krishna and Chandrasekaran and Srivastava—who were here were able people, so they've got a very vigorous group there that is recommending how to design their dams and all that sort of thing. It's been a very fruitful thing for India; before that, they just didn't do anything''(Housner, interviewed by Prud'homme 1984).

These institutional developments enabled Jai Krishna and his colleagues to host the sixth World Conference on Earthquake Engineering (WCEE) in New Delhi in 1977 (Figs. 27, 28), and again Hudson mentions the political patronage for the conference: "An interesting sideline is that, by the time we had the world conference in Delhi, there was a new prime minister, Indira Gandhi, and she played quite a role in the conference. She gave the opening address. We had a very elegant tea party at her house for the conference officials where she thanked me very much on behalf of her father for starting the laboratory. So that was a remarkable thing. There were just a lot of very lucky things that happened….''(Hudson, interviewed by S. Cohen 1997).

On the advice of Jai Krishna, the Department of Science and Technology of the Government of India established the "Himalayan Seismicity" programme to support numerous research projects on seismology, including strong motion instrumentation in some high seismic areas. A large shake table was built at Roorkee in the eighties.

Unfortunately, impetus behind research support for "engineering for earthquakes" has not been commensurate. In the absence of damaging earthquakes from 1967 to 1988, research into engineering for earthquakes tended to stagnate. Besides Roorkee, other

Fig. 27 Jai Krishna addressing Prime Minister Gandhi and select delegates of 6WCEE (*source*: Prem Krishna)

Fig. 28 Prime Minister Gandhi with select delegates of 6WCEE, including Jai Krishna to the *left* in photo, George Housner to *left* of Krishna (*source*: Prem Krishna*)*

academic institutions remained aloof from earthquake engineering. There were no serious efforts to bring professional engineers within the ambit of earthquake safety, and the professionals tended to view earthquake safety as something for the specialists to address (Jain 2008).

5 Code development

5.1 Seismic zone map

As mentioned earlier in Sect. 3, the first ever seismic zone map for India was published by Kumar (1933). The Geological Survey of India (GSI) published a seismic zone map in 1935 as mentioned by West (1937). Seismic zone maps were also published in a number of articles, e.g., Krishna (1959) and Mithal and Srivastava (1959). However, these remained somewhat academic in nature and were never implemented. In 1958, Indian Roads Congress (IRC) published code provisions for seismic design of bridges, in which it provided a seismic zone map and seismic coefficients.

The seismic zone map was formally published in 1962 (Fig. 29) in the first seismic code (IS 1893–1962) by the Indian Standards Institution (ISI), now Bureau of Indian Standards. This was based on the epicentral distribution of past earthquakes and the isoseismals of such events. Seven seismic zones were provided with areas of potential ground shaking with intensity (Modified Mercalli scale) of: less than V, V, VI, VII, VIII, IX, and X (and above) and termed these as Seismic Zones 0, I, II, III, IV, V and VI, respectively. The zone map was modified somewhat in the 1966 version of the code (Fig. 30) but retained the seven seismic zones. In 1967, a magnitude 6.5 earthquake shook the area around Koyna dam in which 200 persons were killed. The affected area was located in seismic zone I on the prevailing map, and hence, triggered a significant change in the seismic zone map in the 1970 version of the code (Fig. 31). Besides changing the boundaries of the zones, the number of zones was reduced from seven to five: seismic zone 0 was merged with zone I, and zone VI was merged with zone V.

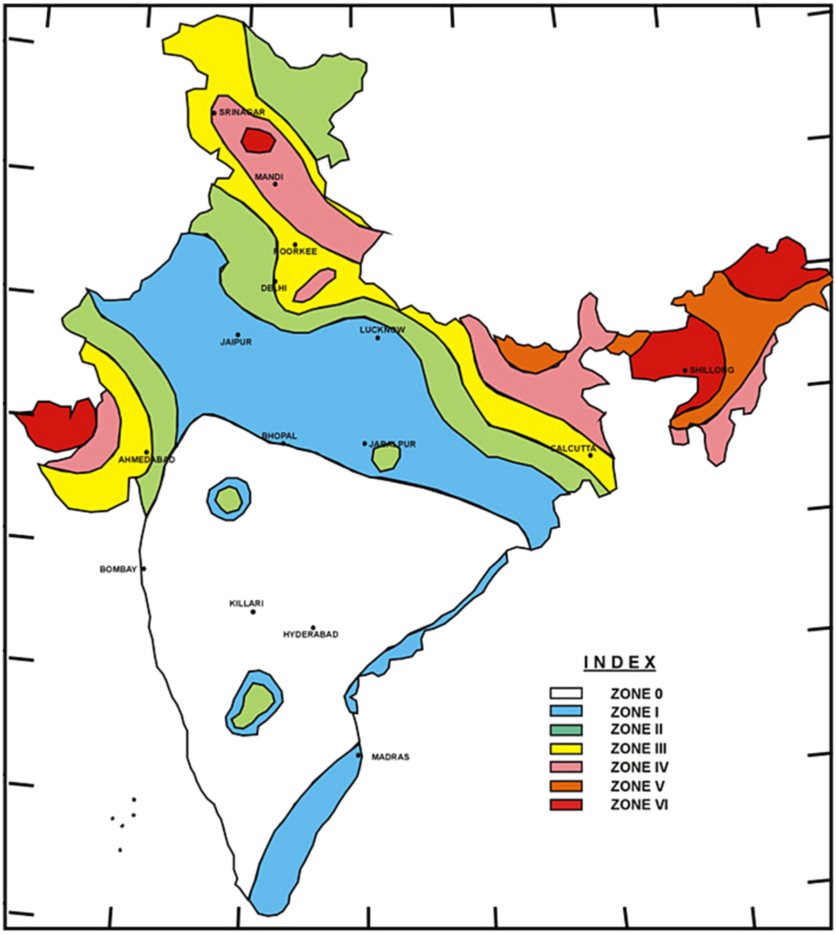


Fig. 29 Seismic Zone Map of India, 1962 (IS 1893: 1962)

Limitations of the 1970 seismic zone map were visible in yet another disastrous earthquake in an area considered of low seismicity. In 1993, the magnitude 6.2 earthquake that occurred in the Latur district of Maharashtra, discussed earlier, had an epicentre near Killari village and killed 7928 persons. The area experienced a shaking intensity of up to IX, even though it was located in seismic zone I which was defined by the code as an area only liable to a shaking intensity of V (or lower) on the Medvedev Sponheuer Karnik (MSK) Intensity Scale. Thus yet another revision to the seismic zone map was triggered by an earthquake. The revised zone map in the 2002 version of IS 1893 further reduced the number of seismic zones from five to four, by merging zone I with zone II. The Latur earthquake-affected area was reconstructed with an ad-hoc decision to comply with seismic zone IV requirements (see Fig. 32). The area was brought under zone III in the 2002 version of the map along with a substantial part of peninsular India.

As can be seen above, the modifications to the seismic zone map in 1970 and again in 2002 have been somewhat ad-hoc, caused by the occurrence of damaging earthquakes in areas considered of very low seismicity. There has been much discussion about the need

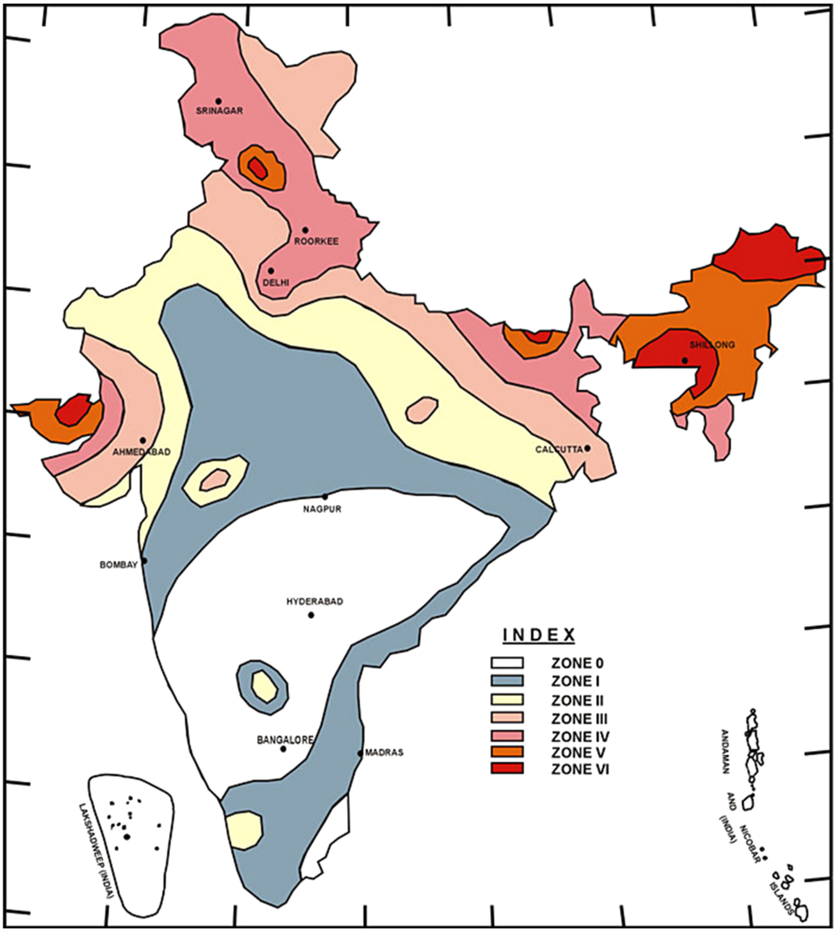


Fig. 30 Seismic zone map of India, 1966 (IS 1893: 1962, revised in 1966)

for a probabilistic seismic zone map for the country and some efforts have been made toward this. The National Disaster Management Authority (NDMA) has undertaken development of such a zone map and under the leadership of Prof R. N. Iyengar, contour maps of peak ground acceleration on A-type rock ($V_{30} > 1.5$ km/s) level for return periods of 500, 2500, 5000 and 10,000 years were prepared in 2011. In 2012, another set of seismic maps (for return periods of 500 and 2500 years) were prepared by a Task Force headed by Dr. B. K. Rastogi set up by the CED39 Committee of the Bureau of Indian Standards. However, not enough discussion has taken place on incorporating any of the probabilistic maps in the seismic codes.

5.2 Early developments of codes

As discussed earlier, in the process of reconstructing Quetta after the 1935 earthquake, seismic codes were developed and implemented for the first time in the Indian subcontinent. However, this effort remained local and did not spread to the rest of India. As a result

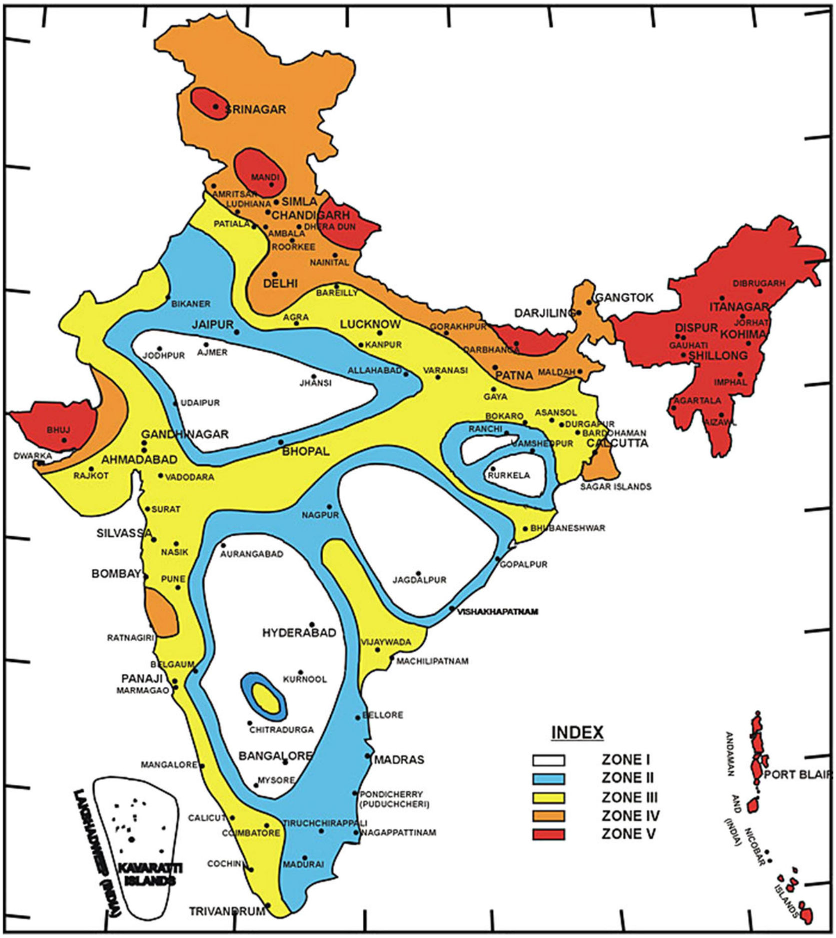


Fig. 31 Seismic Zone Map of India, 1970 (IS 1893: 1962, revised in 1970)

of damaging earthquakes such as those in 1934 Bihar–Nepal, 1935 Quetta and 1956 Anjar (Kutch), some interest was generated amongst professionals towards seismic design and construction. For example:

(a) The Indian Concrete Journal provided very good coverage of the 1934 Bihar–Nepal earthquake damage in a special issue (ICJ 1934) with excellent photographs and captions of the damages.
(b) Design principles of earthquake-resistant buildings were discussed in two articles (ICJ 1956a, b) of the Indian Concrete Journal.
(c) The Concrete Association of India (CAI) published a monograph on earthquake-resistant design in 1954, which was subsequently revised in 1958 and 1965 (CAI 1965).
(d) The Indian Roads Congress (IRC) in Paper No. 112 in 1946 provided for seismic design of bridges situated in regions that are subject to earthquakes (IRC 1946).

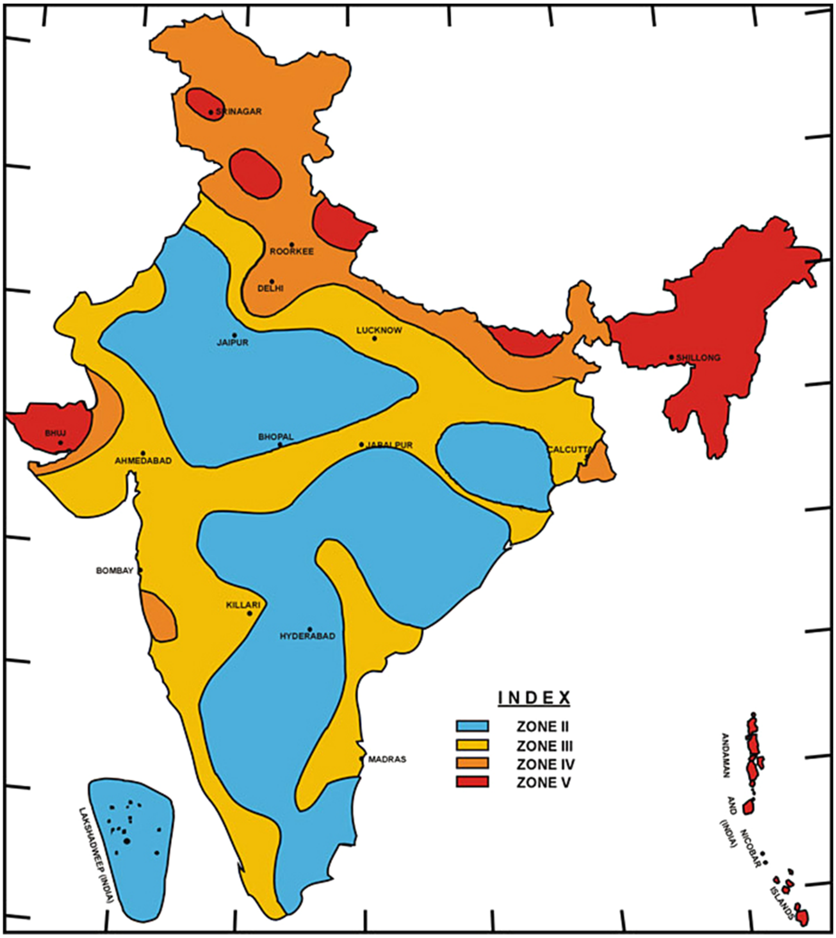


Fig. 32 Seismic Zone Map of India, 2002 (IS 1893: 2002)

(e) 1958 and 1966 versions of the bridge code of the Indian Roads Congress (IRC 1966) provided a seismic zone map for India and specific seismic coefficients for different zones.

While the first formal seismic code in India was published in 1962, the code was not made mandatory for several decades thereafter. Revisions of this code became rather infrequent with the passage of time. Over the years, a number of additional seismic codes have been developed in the country.

After the 2001 Bhuj earthquake, it became clear that Indian seismic codes (and codes for protection against other disasters such as fire and wind) required a significant amount of work. The Gujarat State Disaster Management Authority (GSDMA) sponsored a large project at IIT Kanpur to work on building codes on earthquakes, wind and fire. The scope of work included review of codes, suggestions for modifications in the existing codes, development of several new codes, and development of commentaries and explanatory handbooks. A very significant amount of work was done under this project by a large team of experts from across the country. Under an arrangement with GSDMA, all these documents were placed on the web site of NICEE for wide dissemination (http://nicee.org/IITK-GSDMA_Codes.php). Several of these documents have become the basis of subsequent code revisions.

5.3 Seismic codes from bureau of Indian standards

Table 3 gives a list of the earthquake engineering codes that have been published by the Bureau of Indian Standards. The following notes on the development of these codes provide some context to this table:

(a) IS I893 has traditionally been the main seismic code in India, providing the seismic zone map and seismic design force for different structures, such as buildings, water tanks, stacks, bridges, dams and embankments, and retaining walls. The code, first published in 1962, was revised in 1966, 1970, 1975, and 1984.

(b) The work on revisions to IS 1893–1984 was taken up in 1991 when it was decided to split IS 1893 into several parts with the hope that it would enable more frequent and timely revisions of the code (which unfortunately did not lead to frequent changes). Part 1 of the code contains general provisions (such as zone map, zone factor, etc.) applicable to all types of structures, and specific provisions for buildings. It was published in 2002 and drew heavily from the draft code developed (Murty and Jain 1995) under a project sponsored by the Council of Industrial and Scientific Research (CSIR).

(c) Three other sections of IS 1893 addressing liquid retaining tanks (part 2; published in 2014), bridges and retaining walls (part 3; published in 2014) and industrial

Table 3 Bureau of Indian standards codes on earthquake engineering

Standard no.	Title	Latest version
IS 1893: Part 1	Criteria for Earthquake-resistant Design of Structures—Part 1: General Provisions and Buildings	2002
IS 1893: Part 2	Criteria for Earthquake-resistant Design of Structures—Part 2: Liquid Retaining Tanks	2014
IS 1893: Part 3	Criteria for Earthquake-resistant Design of Structures—Part 3: Bridges and Retaining Walls	2014
IS 1893: Part 4	Criteria for Earthquake-resistant Design of Structures—Part 4: Industrial structures including Stack-like Structures	2005
IS 4326	Earthquake-resistant design and construction of buildings—Code of practice	2013
IS 4967	Recommendations for seismic instrumentation for river valley projects	1968
IS 13827	Improving earthquake resistance of earthen buildings—Guidelines	1993
IS 13828	Improving earthquake resistance of low strength masonry buildings—Guidelines	1993
IS 13920	Ductile detailing of reinforced concrete structures subjected to seismic forces—Code of practice	1993
IS 13935	Seismic Evaluation, Repair and Strengthening of Masonry Buildings—Guidelines	2009
IS 15988	Seismic Evaluation and Strengthening of Existing Reinforced Concrete Buildings—Guidelines	2013

structures (part 4; published in 2005) are now available. The section on dams and embankments is still in process. Part 2 containing provisions on liquid retaining tanks is based on the work done under the GSDMA project (Jain and Jaiswal 2007).

(d) IS 4326 contains general principles for design of buildings, including empirical seismic provisions for masonry buildings. It was first published in 1967 and revised in 1976. It also included some nominal requirements for ductile detailing of reinforced concrete buildings but these were not implemented in practice. This code was revised again in 1993, but the ductile detailing provisions were taken out of this code and included in a new code (IS 13920).

(e) Two new codes, IS 13827 and IS 13828 were published in 1993 containing empirical seismic provisions for (i) earthen buildings, and (ii) low strength masonry buildings, respectively. The rationale was that such housing is common in large parts of India and continues to cause a significant number of deaths in earthquakes. Rather than expecting that such buildings will stop being constructed, it may be better to provide some guidance on improving their earthquake resistance. Much of this guidance was drawn from the 'Guidelines for earthquake-resistant non-engineered construction', published by the International Association for Earthquake Engineering (IAEE 1986).

(f) IS 13920–1993 for the first time provided comprehensive ductile detailing requirements for reinforced concrete structures in regions of high seismicity. This was the result of more than a year-long effort with special funding provided by IIT Kanpur (Medhekar et al. 1992; Medhekar and Jain 1993). A revised version based primarily on work done under the GSDMA project is about to be printed as of January 2015.

(g) IS 13935 when published in 1993 was titled Indian Standard Guidelines for Repair and Seismic Strengthening of Buildings; again much of it was drawn from the IAEE guidelines on non-engineered construction (IAEE 1986). This code was revised in 2009 with the modified title of Indian Standard Guidelines for Seismic Evaluation, Repair and Strengthening of Masonry Buildings. It now contains a relatively simplistic rapid visual assessment method, wherein, depending on the material used in the building, its expected damage category in different seismic zones is indicated.

(h) IS 15988 was published in 2013 based on the work done by Professor Durgesh C. Rai at IIT Kanpur for the GSDMA project for seismic evaluation and strengthening of existing buildings (Rai 2005).

5.4 Seismic codes for the design of bridges

The design of highway bridges in India is governed by the codes of Indian Roads Congress (IRC), and of railway bridges by the Bridge Rules of Indian Railways. Since both provide seismic provisions, the BIS code provisions on seismic design of bridges are not commonly used. However, in some instances, the client may require that the railway bridge must comply with the more conservative of the provisions of the BIS code and Bridge Rules.

The IRC: 6 (Indian Roads Congress 1966) provides requirements on loads and stresses for the design of highway bridges. The code was first published in 1958 and has been revised from time to time. The 1958 version provided three seismic zones with design seismic coefficients as zero, 5 %g, 10 % g, respectively, for the first three zones. Further, the zone map also marked out several epicentral tracts based on the occurrence of past earthquakes; for such areas the design coefficient was left at the discretion of the engineer responsible for the design. In 1979, the code adopted the seismic zone map of IS 1893 with the five seismic zones, and provided design seismic coefficients that depended not only on seismic zones, but also on the importance of the bridge and the type of soil and foundation system.

The collapse of the 56 m span Gawana bridge in the 1991 Uttarkashi earthquake caused significant disruption for several days to a strategic road and stranded the pilgrims at Gangotri. Seeing the inadequacy of seismic code provisions based on this collapse, a proposal was submitted to the Ministry of Surface Transport (MOST) of the Government of India to seek funds to undertake a systematic study on the state of the art of seismic design of bridges across the world, and to develop draft Indian codal provisions. The study was sponsored by the MOST after the 1993 Latur earthquake and enabled systematic study of the issue and development of a draft of a modern seismic code (Murty and Jain 1997, 2000; Jain and Murty 1998). A number of 1-week continuing education programmes were also conducted at IIT Kanpur starting in 1996 on the seismic design of bridges that were attended by a significant number of professional engineers.

As a result of this study and the training programmes, the flexibility of bridges (fundamental natural period) was included in 2003 in consideration of the seismic design coefficient. *Interim provisions* for seismic design were approved by the IRC in 2003 that provided for a seismic coefficient depending on seismic zone, flexibility of the bridge, and type of soil. These provided for a fixed value for the response reduction factor (R) as 2.5 regardless of the type of bridge and for all parts of the bridge, and required that ductile detailing be carried out for bridges in high seismic zones. In 2010, more detailed seismic provisions were adopted by IRC wherein the response reduction factor (R) varies from 1.0 to 4.0 depending on the type of substructure and bearings. It was only in 2011 that IRC codes moved from working stress design to limit state design for concrete structures (IRC 2011), and hence in 2014, the seismic provisions were further revised to make these consistent with limit state design.

Until recently, the seismic design provisions of the Indian Railways continued to provide a seismic design coefficient that was independent of the flexibility of the bridge. A study was sponsored by the Research Design and Standards Organisation of the Indian Railways at IIT Kanpur to develop modern seismic provisions for railway bridges supported by commentary and explanatory examples. This resulted in development of IITK-RDSO Guidelines on Seismic Design of Railway Bridges in 2010 (Jain et al. 2010a, b). Indian Railways had a number of consultations and discussions on this document and in January 2015 formally approved a modified version of it with lower seismic design forces as RDSO Guidelines for Seismic Design of Railway Bridges (RDSO 2015).

5.5 The way forward

The above discussion illustrates that there has been a very significant disconnect and time lag between the development of seismic design codes in India with respect to developments in earthquake engineering elsewhere. For instance, until 2003 the IRC provided for a seismic design force on highway bridges that did not depend on the flexibility (natural period) of the bridge. Similarly, seismic design forces for railway bridges remained independent of structural flexibility until 2015. The BIS codes too have been slow to update; in some cases more than two decades lapse between revisions. This state is a reflection of several challenges in India. To begin with, there are too few experts in earthquake engineering for India's needs. Further, many experts do not appreciate the time and effort needed for development of codes. When codes are not updated in a timely manner, the gap between state-of-the-practice in India vis-à-vis other seismic countries increases disproportionately. Indian professionals' knowledge thus becomes dated and the learning curve to understand needed changes in theory and practice becomes too steep, resulting in higher resistance to changes. To enable the professionals to appreciate changes in the code and implement these smoothly, it is important to simultaneously develop commentaries and explanatory handbooks. All this requires a significant amount of work requiring funds, and cannot be carried out by voluntary committee membership alone. A substantial amount of work on codes was carried out at IIT Kanpur because funding for this purpose became available from a number of agencies such as Council of Scientific and Industrial Research (CSIR), Ministry of Surface Transport (MOST), Gujarat State Disaster Management Authority (GSDMA) and Research Design and Standards Organization (RDSO). If the country is to catch up with other developed seismic countries in this area, appropriate funding must be allocated by the concerned organizations for development of seismic codes.

The codes of practice are useful only if these are implemented in actual construction. Until 2001, the seismic codes in India were not mandatory and were only recommendations. After 2001, many cities and states started to require compliance with seismic codes. However, most often there has been no enforcement and no mechanisms exist in most of the country to prevent someone from constructing a building that does not comply with the codes. While on one hand, the country must work on regular updates of the codes, on the other hand, it is even more critical to create mechanisms for implementation and enforcement of the existing codes.

6 Capacity-building initiatives

Capacity-building initiatives in earthquake engineering have been in place in India in some form for decades. The Government of India, particularly through its Ministries of Human Resource Development and Home Affairs, has been involved in various capacity-building initiatives, as have state governments and the various IITs, colleges, universities and many non-governmental organizations (NGOs). These initiatives can range from professional development programmes, to training of masons, including the development of handbooks and guidelines, to awareness-building workshops to technical short courses. The need for such initiatives has become particularly apparent after recent major earthquakes, where post-earthquake damage surveys illustrate widespread use of unsafe design, detailing and construction practices. These earthquakes make it clear that there is a need for more knowledge for everyone involved all along the chain of the construction process, from the building owner, the architect, the engineer, the contractor, the mason and the municipal official. Hundreds of damaged and collapsed building sites tell the same disturbing story—poor architectural configuration, inadequate structural design, lack of proper detailing and poor construction and inspection practices. The stakeholders are many and include not only those directly involved in design, construction and management, but the community as a whole. An aware and sensitized community is an important cornerstone of a strong earthquake risk reduction program. However, the awareness and concern of a community towards safety must be supported by competent professionals. Hence, it is critically important to undertake capacity-building of professionals engaged in design and construction, particularly structural engineers and architects.

While there are many types of capacity-building initiatives targeted at many different stakeholders, this section will focus on several particularly successful initiatives targeted at professional engineers and architects and at colleges of engineering and architecture. An interesting and happy coincidence actually contributed to this. In the 1980's a group of young structural engineers trained in earthquake engineering in some leading universities overseas joined the IITs as regular faculty members to teach structural engineering (Jain 2008). They brought to the institutes their research interests in earthquake engineering and the discipline grew.

6.1 Continuing education programmes

Early in the 1990s it was apparent that numerous practising structural engineers in the country, notwithstanding excellent education and training in structural engineering, did not understand concepts of earthquake-resistant construction. In October 1992, a 3-day course on "Seismic Design of Reinforced Concrete Buildings" for professional engineers was conducted by the author together with Prof CVR Murty[2] as an inaugural programme to kick-start formal activities at the new IIT at Guwahati[3] (Fig. 33). Based on feedback from that course, a massive campaign was then launched to train professional engineers in earthquake engineering. Typically, the programmes were (a) of 5-day duration, (b) taught by just two or three instructors (as opposed to a large number of speakers), and (c) self-supporting wherein the entire costs were met from the registration fee charged to the participants. While many academics and postgraduate students participated in these courses, the emphasis was on practising professionals. Therefore, concepts were explained in physical terms without resorting to complex mathematics.

In the initial courses, there was tremendous resistance amongst the professionals to accept concepts of earthquake-resistant design. For instance, an engineer with 20 years of professional practice would usually find it very unsettling to learn that his analysis, design or detailing methods were inadequate. Over the years this resistance reduced, and by the time of the 2001 Bhuj earthquake a significant number of professionals in the country had become familiar with earthquake design. Between 1992 and 2002 about 2000 professional engineers were trained in seismic design courses conducted in different parts of India, Nepal and Bhutan. Collapses of numerous buildings in the Bhuj earthquake significantly reduced the resistance that professionals had towards earthquake design concepts.

Over the years, a large number of other continuing education programmes in earthquake engineering have been organized at the various IITs, including IIT Roorkee which has had a programme for the last 40 years, IIT Kanpur which has had a very active programme in the last two decades, and IIT Gandhinagar which began a series of continuing education programmes in 2011. These programmes have been extremely valuable in taking earthquake engineering concepts to professionals, and significant improvements have taken place in the construction practices in the country as a result of these. For instance, in 1999 it was heartening to see in the small town of Imphal (in highest seismic zone V) several

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[2] Prof CVR Murty, at that time teaching in IIT Delhi, was to later join IIT Kanpur and work closely with the author for more than a decade.

[3] Establishing an IIT in the state of Assam was one of the commitments made by the Government of India in the Assam Accord, signed on August 15, 1985, under the Prime Ministership of Rajiv Gandhi. The Foundation Stone of the Institute was laid on July 4, 1992, by the then Prime Minister PV Narasimha Rao. The 3-day course was held soon after this and long before the new Institute admitted its first batch of students in July 1995.

Fig. 33 Participants in the short course at IIT Guwahati in 1992, three years before the undergraduate admissions commenced (*source*: author)

buildings under construction with seismic detailing of reinforcement as a result of the efforts of course participants (Jain and Murty 2003; Jain 2010).

6.2 Two workshops at Kanpur

What if a group of select academics and professionals were to meet at one place for three days and have free across-the-table discussions, without a rigid agenda and without having any formal presentations? This simple question over a casual conversation resulted in two brain-storming workshops at IIT Kanpur that later proved very effective towards capacity-building for seismic safety.

The first such workshop on the broad theme of earthquake-resistant construction in a civil engineering curriculum (Murty et al. 1998) was held during 10–12 October 1996 at IIT Kanpur. It was recognized that a typical undergraduate civil engineering curriculum did not include any coverage of earthquake engineering; this was also the case even at the post-graduate level, and only a small fraction of structural engineering students got a chance to study earthquake engineering and design. Hence, most civil engineers were not receiving any formal training in earthquake engineering. The questions that prompted the 1996 workshop give a glimpse of the state of affairs in India at that time (Murty et al. 1998):

- Should we continue to let earthquake-resistant constructions be handled by specialists only, or should an average civil engineer responsible for construction be expected to know about appropriate earthquake technology for day-to-day constructions?

- Should earthquake-resistant construction be taught as a separate subject in the engineering curriculum, or should the topics related to earthquake engineering be merged with the existing courses?
- Should earthquake engineering maintain an identity outside the normal civil engineering industry or become a part of civil engineering industry itself?
- How best to achieve the following goal: professional civil engineers should be able to ensure earthquake-resistant constructions without seeking help from "earthquake engineering experts," particularly for the run-of-the-mill constructions.

The workshop participation was by invitation, and 19 persons from across the country, representing academia, industry, and R&D laboratories, participated in intense discussions over three days. Numerous ideas emerged, clarity was obtained on many issues, and a number of recommendations pertaining to earthquake engineering in general, and the civil engineering curriculum in particular emerged from the workshop.

The second such workshop on "Developing Earthquake Engineering Industry in India: Opportunities & Challenges" was organized at Kanpur during 14–16 October 1998 and included 22 participants from across the country and of diverse backgrounds (Murty et al. 1999). The main question that this meeting addressed was: *challenges ahead and opportunities available for developing an earthquake engineering industry wherein earthquake-related services and products can be conveniently available.*

Besides generating numerous excellent recommendations and providing clarity to many fuzzy ideas, the workshops enabled a group of enthusiasts to spend time together, know each other, and form a community. These turned out to be preparatory meetings that led to two major initiatives in India discussed below: the establishment of the National Information Centre for Earthquake Engineering (NICEE) at IIT Kanpur in 1999, and the National Programme on Earthquake Engineering Education (NPEEE) conducted during 2003–2007. Thanks to the vision and clarity provided by these workshops, it was possible to leverage the opportunity provided by the 2001 earthquake. The informal network and the community that emerged out of these meetings were critical for the implementation of these new initiatives. Looking back, the investment of time and money on these two meetings could be termed as amongst the best investments made by the author in his professional career.

6.3 National information centre of earthquake engineering (NICEE)

6.3.1 Inception

One of the key observations from the 1996 workshop at IIT Kanpur was that the gap between the international state-of-the-art and that in India had been widening with time. A major contributor to this situation was the non-availability of books, journals and other technical reports to Indian academics and professionals for various reasons (Jain and Murty 2003). The workshop recommended that a national resource centre be created to enable anyone anywhere in the country to borrow books and reports.

A proposal for creating the National Information Centre of Earthquake Engineering (NICEE) at IIT Kanpur was developed in 1997. It was proposed that the Centre would be funded through interest income from an endowment and other incomes, and that it would operate within the overall financial and administrative framework of IIT Kanpur. The focus of the proposed Centre was on creating a library-oriented resource centre; the following objectives were outlined in the original proposal:

(a) To keep track of availability of new publications and other materials in the area of earthquake engineering.
(b) To create and maintain a decent storehouse of publications and other materials on earthquake engineering.
(c) To disseminate information about availability of the above material at IITK to interested professionals, researchers and academicians, and,
(d) To make available the material to interested persons in a timely manner.

A strong endorsement by Professor N. C. Nigam, the then-President of the Indian Society for Earthquake Technology and Vice Chancellor of the University of Roorkee (now IIT Roorkee) to the proposal was critically helpful to raise funds for the Centre. In the first instance, an endowment of Rs 5 million (~€90,000)[4] was raised from four organizations: Housing and Urban Development Corporation (HUDCO), Telecom Commission, Railway Board, and Ministry of Agriculture of Government of India. In addition, the Board of Research in Nuclear Sciences (BRNS) provided a recurring grant for 3 years towards the Centre.

After the first grant was received from HUDCO in 1999, a modest level of activities of the Centre started without making a formal announcement. However, the 2001 Bhuj earthquake created an unprecedented urgency and the focus shifted from fund-raising to information dissemination. Within a few days of the earthquake, NICEE web site was launched with IAEE guidelines on non-engineered constructions (IAEE 1986) as a key resource and it was widely accessed by engineers in Gujarat.

6.3.2 The centre

Even though housed within IIT Kanpur, NICEE operates as a national resource. A number of colleagues in the country (and outside) provide leadership in various activities of the Centre. The Centre is managed by a National Advisory Committee consisting of representatives from different institutions in the country, industries, and individuals; the Committee meets annually, reviews activities of the Centre and provides guidance and advice.

In its early days, a number of organizations and individuals provided their publications or other resources as a gift, e.g., Multidisciplinary Centre for Earthquake Engineering Research (MCEER) at Buffalo (USA), Earthquake Engineering Research Institute (EERI) in USA, New Zealand National Society for Earthquake Engineering (NZSEE), the late Professor George Housner of the California Institute of Technology Pasadena, and the late Professor N C Nigam in India.

The Centre was conceived so as to minimize its operational costs, by utilizing the infrastructure and the administration of IIT Kanpur. For instance, all books and publications procured by the Centre are placed in and managed by the Central Library of the Institute, and IIT Kanpur handles all administration, accounts and audits in the usual manner.

The Centre currently incurs expenditures of the order of Rs 4 million (~€60,000) per year, which it covers by donations, sponsorships, interest earnings of its endowment, and the sale of publications. To date, about 500 unique donors have made contributions to the Centre, with an average contribution of Rs 15,000 (~€200) and a median contribution of

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[4] In order to give perspective to the reader, value in euros has been provided here (and in the rest of the paper) based on the contemporary value of euro.

Rs 3000 (~€40). The NICEE publications are priced very nominally and many are distributed free of charge.

With time, the scope of NICEE activities has been enlarged considerably, from the initial intent of a library-oriented Centre, to a Centre that undertakes a number of outreach and capacity-building activities. Some of its important activities are described in the following section.

6.3.3 Activities

Table 4 lists the components of the various activities that NICEE has engaged in since 2001.

6.4 National programme on earthquake engineering education

6.4.1 Inception

Extensive media coverage of the enormous loss of life and damages after the 2001 Bhuj earthquake brought the reality of the earthquake disaster into sharp focus, and as a shocked nation became more receptive than ever before to the devastation of an earthquake disaster, the ground was laid for capacity-building initiatives directed at earthquake safety. The preparatory work through deliberations at the 1996 Workshop at IIT Kanpur described above were effectively leveraged to get an ambitious pan-India project for capacity-building in colleges of engineering and architecture in the area of earthquake engineering. This section describes the National Programme on Earthquake Engineering Education (NPEEE) supported by the Ministry of Human Resource Development (MHRD), Government of India and managed by the seven IITs and the IISc Bangalore during 2003–2007, with IIT Kanpur providing overall leadership.

In view of the enormous disaster, the Prime Minister appointed a senior official as Secretary of Disaster Management in the Cabinet Secretariat to coordinate the situation on behalf of the Government of India. In a meeting with him, the author emphasized that Indian engineering colleges and universities needed to upgrade themselves in the discipline of earthquake engineering. This official took up the matter of training of teachers in earthquake engineering with the Secretary of Higher Education in the MHRD. As a result, in August 2001 the MHRD called a meeting with representatives of premier academic institutions, research institutions, and other ministries and organizations concerned with seismic safety, to discuss the issue at a holistic level. A consensus was reached that there was a need to build capacity in earthquake engineering within academic institutions. A proposal was developed for a National Programme on Earthquake Engineering Education, wherein the seven IITs and the IISc would form a consortium as resource institutions to undertake the task. The proposal was circulated by the MHRD to other concerned Ministries and Departments for their feedback and comments. In August 2002, the Standing Finance Committee of the MHRD cleared the project and the Ministry released the first grant for NPEEE in March 2003. Project activities started immediately thereafter, with a launch workshop held at IIT Delhi on April 5, 2003 (Fig. 34). The project continued to March 2007 and concluded with another workshop at IIT Delhi on January 5, 2007 to look back and review the progress over the 4-year period.

Table 4 Key components of NICEE

Activity	Component
Communication and dissemination	Centre's web site (www.nicee.org) launched immediately after the 2001 earthquake; As of January 2015, ~35,000 access/day, with more than 1220 MB/day downloads A monthly electronic newsletter to more than 12,000 persons as of January 2015 Articles and other literature either free of charge or for a very nominal charge
e-conferences	Commemorated first anniversary of the 2001 earthquake by organizing a 2-week e-conference on "Indian Seismic Codes" (January 26 to February 8, 2002). About 1200 persons participated; about 100 persons from ten countries made about 300 postings during the 2 weeks, and numerous issues on Indian codes were resolved or articulated (Rai and Sheth 2002) During August 26–31, 2002s e-conference on "Professional Issues in Structural Engineering in India". Received an enormous response Both e-conferences clearly showed the need for forum to electronically discuss and share ideas Resulted in creation of an independent discussion forum "Structural Engineers Forum of India" to mark second anniversary of Bhuj earthquake (www.sefindia.org)
Publications	Publishing and distributing numerous books and monographs at nominal charge or free-of-cost Distributes inexpensive Indian reprints of many useful publications with permission of the original publishers Video recordings of lectures or power point slides on a given topic disseminated as CD's Translations of important publications in regional languages To 2014, about 90,000 copies of publications distributed
Quarterly journal	Built on premise that continuous flow of current information is critically needed Started quarterly periodical "Earthquake Engineering Practice" wherein already published articles of other reputed journals (with due permissions, with possibly some delay) are included Articles particularly from EERI's Earthquake Spectra and Bulletin of New Zealand National Society for Earthquake Engineering Distributed on system of "voluntary price"; one has option to receive free of charge or for nominal price As of 2014, more than 3400 subscribers receive the Practice free of charge, including 300 individuals overseas from 68 countries
World conference proceedings	The International Association for Earthquake Engineering (IAEE) been sponsoring a World Conference in Earthquake Engineering (WCEE) once every 4 years since 1956 Number of conference papers increasing year after year; for instance, proceedings of the 15th conference in Lisbon in 2012 contains more than 3300 papers At request of IAEE, NICEE undertook a massive project to put all world conference papers on website Included scanning 5360 research papers (about 40,000 pages) from first ten conferences All available on NICEE website for free access

Table 4 continued

Activity	Component
Distribution of ETABS and SAP to colleges	NICEE negotiated with Computers and Structures Inc, Berkeley, USA to donate their software ETABS and SAP free of charge to engineering colleges in the country To date more than 250 colleges availed themselves of this opportunity
Annual earthquake engineering review workshop for master's students	In 2001 started an annual 1-week literature review workshop at IIT Kanpur for graduate students pursuing thesis in earthquake engineering from across the country To date more than 650 students from 70 colleges in India and Nepal have participated In addition to literature survey, participants get to meet faculty and students of IIT Kanpur, tour laboratory facilities (Jain and Murty 2003)
Annual workshop for architectural students	In 2008 started annual workshop at IIT Kanpur for architectural students (see discussion in Sect. 6.5.4)
Inter school quiz for children	In 2009 started annual quiz on earthquake safety for school children Based on Earthquake Tips More than 350 schools in 50 cities in the country have participated to date

Fig. 34 Participants in 2013 literature review workshop for earthquake engineering graduate students (*source*: NICEE)

6.4.2 The programme

The programme was open to all colleges/polytechnics of engineering or architecture, privately or publicly funded. The programme had a limited focus—training of faculty (of colleges of engineering and architecture, and of polytechnics) and curriculum development. At that time, India had 1000+ institutes teaching civil engineering or architecture at diploma, undergraduate or postgraduate levels. Most of these were not teaching earthquake engineering elements in the curriculum and had varying levels of earthquake engineering expertise within their faculty. While outreach activities such as organizing workshops and development of teaching laboratories were supported, the programme was not meant to support research and development in earthquake engineering. It was felt that supporting research and development might cause a loss of focus, and in any case there were other concerned Ministries of the Government of India to support R&D.

Initially the project was approved for a 3-year duration with a budget of Rs 137 million (about €2.5 million at that time); the duration was later extended to a fourth year, even though champions of the project felt that the project should continue for at least 10–20 years to make a full impact. All eight resource institutes that operated the programme had regular operating expenses fully funded by the same ministry (MHRD); hence, the budget did not include salaries, buildings or any administrative costs.

NPEEE was administered through the National Committee on Earthquake Engineering Education (NCEEE). This Committee was responsible for overall monitoring of NPEEE, and for coordination with other Ministries/Departments and the All India Council for Technical Education (AICTE). NPEEE was steered through a Programme Implementation Committee (PIC) and a number of its sub-committees. Amongst the eight resource institutions, IIT Kanpur was designated as the nodal institute for effective implementation and the author was designated as the National Coordinator for NPEEE (see Fig. 35; the launch workshop of NPEEE). The Programme Implementation Committee (PIC) was responsible for (a) ensuring timely and effective implementation, (b) allocation of activities to different resource institutes and ensuring inter-institutional coordination, (c) selection of colleges and trainees for various activities, and (d) all other matters related and incidental to implementation of the programme. This included reviewing (a) the lists of participants, (b) summaries of course evaluations, (c) test question papers and assessment scores, and (d) the materials used in the courses (Jain and Agrawal 2004). The director of one of the resource institutes chaired NPEEE, and its membership consisted of representatives of the eight resource institutions, and one representative each from an engineering college, an architecture college, and a polytechnic. To ensure transparency in its activities and financial operations, a detailed Project Implementation Plan (PIP) was developed very early on, along with a website; both proved to be important tools for effective implementation of the programme. The PIP provided all details of the programme, including a detailed budget and financial norms. A fairly large email list of about 1500 faculty members was developed.

The Programme could be a useful model for capacity-building in earthquake engineering (and in fact in any other discipline) in many developing countries, and hence, some of its core components are described in Table 5 below.

6.4.3 Outcome

The programme achieved most of its targets, and in some sense, even exceeded the expectations of the proponents. To evaluate the programme, a survey was conducted in December 2005 to which 94 colleges, and 177 teachers responded. The results were quite positive:

(a) NPEEE has been useful in capacity-building of colleges and teachers: Average response 4.62 (out of maximum 5.0) from the colleges, and 4.76 from the teachers.
(b) The Programme has operated well: Average response 4.40 (out of maximum 5.0) from the colleges, and 4.65 from the teachers.
(c) The Programme should continue: Average response 4.84 (out of maximum 5.0) from the colleges, and 4.91 from the teachers.

Table 5 Key components of NPEEE

Activity	Component
Short-term training	One to four week training programmes conducted for interested faculty members from engineering colleges, polytechnics and architecture colleges Short-term training enabled college administrators to send their teachers for training without compromising their semester teaching responsibilities Particularly useful to give an initial exposure to earthquake engineering, as well as for higher-end specialized topics In all, 1360 teachers received a total of about 1900 person-weeks of training under this programme Costs connected with training, including boarding, lodging and travel of faculty members covered by programme funds
Longer-term training	Three of the resource institutions also conducted one-semester certificate courses in Earthquake Engineering 59 teachers trained Courses treated as continuing education programmes with regular homework assignments and examinations Certificate awarded to teachers on successful completion Many teachers with postgraduate degrees found one-semester programme to be very useful to develop in-depth expertise in earthquake engineering Costs connected with training, including boarding, lodging and travel of faculty members covered by programme funds
Library support	Programme provided earthquake engineering books and publications (worth Rs 100,000, about ~€1800 per college) to 100 colleges in the country Colleges were selected based on their faculty expertise and ongoing activities in earthquake engineering The books were procured centrally and shipped to the colleges The eight resource institutes also each provided with a sum of Rs 300,000 (~€5400) for enhancing their own library resources
Laboratory support	Ten colleges, selected on basis of credentials in earthquake engineering, provided with a sum of Rs 1.5 million each (about €27,000) to develop basic teaching laboratories Colleges made their own decisions on equipment, allowing for flexibility to meet their own needs and requirements 8 resource institutes provided with a sum of Rs 5 million (about €90,000) each to enhance their teaching and research laboratories
International opportunities	Funds provided for visits of 7 overseas academics (from Canada, New Zealand, Slovenia, and USA) to resource institutions for duration of about 1 month Partial travel grants (up to Rs 50,000, about €900) provided to Indian academics to attend international conferences (76 teachers used these grants) 9 young teachers were sent to overseas universities (in Canada, Japan, New Zealand, UK and USA) for 6-month post-doctoral research opportunities Collaborative activities resulted from visits of international academics from overseas. For example, during visit of Professor Svetlana Brzev to IIT Kanpur a new monograph (Brzev 2008) was developed on Confined Masonry, and this provided the seed to grow the activities to propagate the use of confined masonry in India and elsewhere (See Sect. 8)

Table 5 continued

Activity	Component
Development of curricula and resource materials	Number of workshops were conducted and proceedings widely circulated on curricula for undergraduate programmes and diplomas in civil engineering and architecture (Murty et al. 2004; Jain et al. 2004) Developed resource materials for a teaching laboratory in earthquake engineering which included (a) students manual, (b) a teachers manual, and (c) fabrication manual with all details so typical college could develop the experimental set-ups at a very low cost Manual made available for free download on NPEEE web site and provided on a CD. Used by number of colleges to develop their own teaching laboratories Government of Gujarat sponsored a programme wherein L D College in Ahmedabad developed the standard teaching laboratory for earthquake engineering that was procured by 25 colleges in Gujarat
Development and distribution of RESIST	Software RESIST (developed by Prof. Charleson in New Zealand) helps architecture students integrate structural issues in their designs NPEEE sponsored an Indian version of RESIST and distributed this to the colleges (see discussion in Sect. 6.5.2)
Conferences and outreach	Funded, fully or partially, large number of conferences and workshops organized by resource institutions, in earthquake engineering and related areas Supported outreach activities by the colleges through workshops, trainings, and conferences

A good number of colleges started to teach earthquake engineering. The 2005 survey indicated that (a) 69 colleges out of the 94 colleges that responded teach earthquake engineering, and (b) 117 teachers, out of the 177 who responded, indicated that their respective colleges teach earthquake engineering.

The success of the Programme can be attributed largely to transparent administrative mechanisms, non-discriminatory policies with regard to private versus government funded institutes, a feasible and manageable domain of operations, and its human resources that drew upon strongly motivated and committed individuals working as a cohesive team. A very significant amount of capacity was built as a result of the Programme in the incorporation of earthquake engineering in engineering and architectural education that will pay rich dividends in the years ahead.

6.5 Interventions towards the architectural profession and education

Architects have a critical role to play in ensuring earthquake resistance in the built environment since they occupy a key position in project conceptualization, planning and implementation, coordinating various professionals from different disciplines. Poor conceptual design and detailing of various elements by the architect will seriously impair the ability of structural and construction engineers to incorporate earthquake resistance in a building. To quote the renowned earthquake engineer, the late Henry J. Degenkolb (1977):

> If we have a poor configuration to start with, all the engineer can do is to provide a band-aid – improve a basically poor solution as best as he can. Conversely, if we start off with a good configuration and a reasonable framing system, even a poor engineer can't harm its ultimate performance too much.

Charleson (1997) refers to a study that confirmed the view that the *architectural concept may be more detrimental to the seismic survival of a building than any other design decision*. It is therefore imperative that architects understand and appreciate the concepts of earthquake-resistant design.

A number of initiatives have been undertaken in India to bring the architectural community, including professionals, faculty, and students, within the ambit of earthquake safety. As a result, many architectural colleges are also now addressing the subject of the earthquake performance of buildings.

6.5.1 Earthquake-resistant curriculum in architecture colleges

A strategic decision was made in formulating the National Programme on Earthquake Engineering Education (NPEEE) to include the colleges and faculty of architecture on a par with colleges and faculty of civil engineering. This was critically beneficial towards bringing earthquake engineering to the colleges of architecture; a number of curriculum workshops were held to bring earthquake safety into the architectural curricula (e.g., Jain et al. 2004), and a number of faculty members from architectural colleges were trained under the programme. The task of introducing changes in the architectural curriculum is a bit more challenging than doing so with the civil engineering curriculum. The concepts of the earthquake behaviour of buildings need to be innovatively linked to the process of architectural design for the students to develop an appreciation of the same. As a result of this effort, earthquake-resistant architecture has been included in the academic curriculum of a number of undergraduate colleges of architecture in the country.

6.5.2 Resource materials for architects

It was recognized that appropriate resource materials must accompany curriculum changes and innovations suggested under the NPEEE. A number of books and other resource materials were made available; several were developed particularly for this purpose:

- IITK-BMTPC Earthquake Tips, described below, were mailed by NICEE to about 10,000 professional architects in India free-of-charge. Subsequently, the Tips were included in the professional directory of the Indian Institute of Architects (IIA) to ensure that every architect member of IIA will have the Tips readily available on his or her bookshelf.
- A special project was undertaken by Prof. C. V. R. Murty (of IIT Kanpur) and Prof. Andrew Charleson (of Victoria University of Wellington in New Zealand) under the sponsorship of NPEEE under which they developed ~600 Power Point slides with notes. These are meant to enable teachers within architecture schools to cover the model curriculum for architecture students in 27 lectures. These are distributed both in hard and soft copy format (Murty and Charleson 2006).
- NPEEE sponsored a special project by Professor Andrew Charleson wherein he developed an Indian version of RESIST software (that he had originally developed for use by students in New Zealand) for use by architectural students in India. The programme enables a student to get a rough idea of the sizes of frame elements or shear walls needed for a building design project, given the wind and seismic zones in which the building is located. It is a very useful tool to sensitize the students to start thinking of adequate structural sizes while planning the building, and has been distributed to most of the architectural colleges in India.

6.5.3 Ministry of home affairs seminars

A series of seminars throughout the nation were organized in 2004 and 2005 as a joint programme with the Ministry of Home Affairs, Government of India and the Continuing Education Programme of the Indian Institute of Architects on "The Role of Architects Towards a Seismically Safe Built Environment". The concept and the content for the one-day seminar was developed in consultation with faculty at IIT Kanpur. The seminar consisted of lectures by one resource person from a structural engineering background and one from an architectural background. The participants were also provided sufficient reading materials.

The Institute organized 21 one-day seminars across the country, often with Relief Commissioners, Disaster Management Departments and United Nations Development Programme (UNDP) state units. Approximately 110–150 architects (professional architects as well as faculty members in architectural schools) attended each of the 21 seminars, and approximately 2700 architects benefitted from this seminar series.

6.5.4 Annual workshop for architectural students at IIT Kanpur

Starting in 2008, an Annual Workshop Series was developed by NICEE to directly reach undergraduate students of architecture so as to achieve intense knowledge transfer and capacity-building of the architects of tomorrow. The workshop consists of sensitizing the students in earthquake-resistant design practices through technical lectures followed by design studios where they are given hands-on guidance in earthquake-resistant design by working on an architectural design project in Time Sketch, a format with which they are familiar. The workshop is conducted by architecture and structural engineering faculty and professionals with expertise in and commitment to an earthquake resilient built environment. The workshop affords the students a unique opportunity to grapple with and strike a balance between the requirements of earthquake-resistant design and a host of design considerations that they normally consider in their architectural design exercises. Nearly three hundred undergraduate students of architecture have participated in seven such workshops since 2008 (Fig. 36). A detailed discussion of this series can be found in Mitra et al. (2013).

6.5.5 NICEE outreach events for architects

NICEE has also engaged with architects and architectural students during their own major events. For instance, NICEE has participated in a number of Conventions of the National Association of Students of Architecture (NASA), wherein presentations are made on different aspects of earthquake-resistant design and on the historical aspects of earthquake-resistant architecture from antiquity to contemporary times. Resource materials have been distributed to the future architects and a quiz has been conducted with cash awards based on the Earthquake Tips, discussed in the next section (Jain 2010). NICEE also participated in the 2008 conference of the South Asian Association for Regional Cooperation of Architects (SAARCH) in New Delhi.

6.6 Earthquake tips

In early 2002, a project "IITK-BMTPC Earthquake Tips" was undertaken at IIT Kanpur with sponsorship of the Building Materials and Technology Promotion Council (BMTPC),

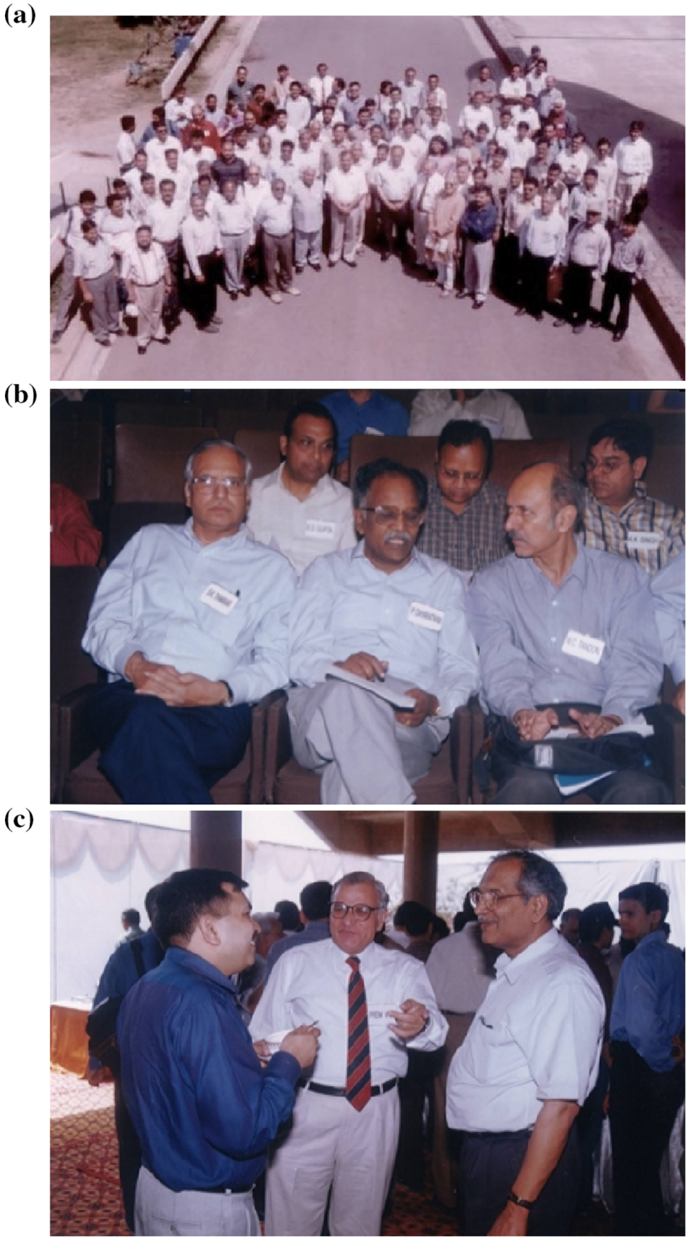


Fig. 35 Launch workshop of NPEEE at IIT Delhi **a** Participants; **b** attendees Prof S. K. Thakkar of IIT Roorkee, Prof P. Dayaratnam of IIT Kanpur and Mr M. C. Tandon of Tandon Consultants in a session **c** Mr Pawan Agarwal of MHRD, Prof Prem Vrat, Director IIT Roorkee, and Prof Rajpal S. Sirohi, Director IIT Delhi in a conversation. (*source*: NICEE)

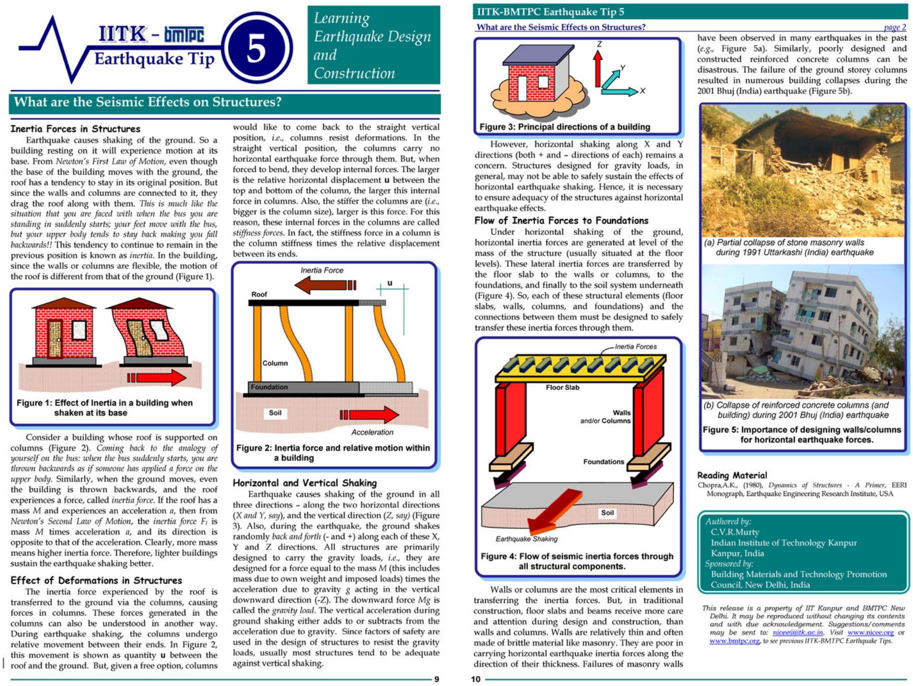
New Delhi (Murty 2005). The 24 Tips, each consisting of two A-4 size pages, provide basics of earthquake-resistant constructions in a simple language so that not only an average civil engineer and architect, but also even an interested citizen, can appreciate the

Fig. 36 Students presenting their design to the jury in the 2008 architectural workshop (*source*: NICEE)

subject (Fig. 37). Topics covered include introduction to earthquakes, concepts of earthquake-resistant design, and aspects of aseismic design and construction of buildings. Every month, one Tip was released for publication to all interested journals, magazines, and newspapers, and placed on the web site of NICEE. A large number of journals of architecture, construction and structural engineering, and many prestigious mainstream newspapers published the Tips. The Tips have been a tremendous success and are very frequently downloaded from the web site of NICEE. Over the years, through voluntary efforts, the Tips have been translated from English into Hindi and Marathi. More recently, the same team has developed an additional set of 8 Tips with sponsorship of BMTPC and these will be released in the near future.

6.7 Other capacity-building initiatives

The regular occurrence every 2–3 years of damaging earthquakes since 1988 has also had its impact on how the Government of India deals with disasters. After the 1999 Orissa Supercyclone, with an official death toll in excess of 8000, the Government of India formed a "High Power Committee" to look into the issues of disasters and to make recommendations. After the 2001 Bhuj earthquake, the subject of natural disasters was moved from the Ministry of Agriculture to the Ministry of Home Affairs, and after the 2004 Sumatra earthquake and tsunami, the National Disaster Management Authority



Learning Earthquake Design and Construction

What are the Seismic Effects on Structures?

Inertia Forces in Structures

Earthquake causes shaking of the ground. So a building resting on it will experience motion at its base. From *Newton's First Law of Motion*, even though the base of the building moves with the ground, the roof has a tendency to stay in its original position. But since the walls and columns are connected to it, they drag the roof along with them. *This is much like the situation that you are faced with when the bus you are standing in suddenly starts; your feet move with the bus, but your upper body tends to stay back making you fall backwards!!* This tendency to continue to remain in the previous position is known as *inertia*. In the building, since the walls or columns are flexible, the motion of the roof is different from that of the ground (Figure 1).

Figure 1: Effect of Inertia in a building when shaken at its base

Consider a building whose roof is supported on columns (Figure 2). *Coming back to the analogy of yourself on the bus: when the bus suddenly starts, you are thrown backwards as if someone has applied a force on the upper body.* Similarly, when the ground moves, even the building is thrown backwards, and the roof experiences a force, called *inertia force*. If the roof has a mass M and experiences an acceleration a, then from *Newton's Second Law of Motion*, the *inertia force* F_I is mass M times acceleration a, and its direction is opposite to that of the acceleration. Clearly, more mass means higher inertia force. Therefore, lighter buildings sustain the earthquake shaking better.

Effect of Deformations in Structures

The inertia force experienced by the roof is transferred to the ground via the columns, causing forces in columns. These forces generated in the columns can also be understood in another way. During earthquake shaking, the columns undergo relative movement between their ends. In Figure 2, this movement is shown as quantity **u** between the roof and the ground. But, given a free option, columns would like to come back to the straight vertical position, *i.e.*, columns resist deformations. In the straight vertical position, the columns carry no horizontal earthquake force through them. But, when forced to bend, they develop internal forces. The larger is the relative horizontal displacement **u** between the top and bottom of the column, the larger this internal force in columns. Also, the stiffer the columns are (*i.e.*, bigger is the column size), larger is this force. For this reason, these internal forces in the columns are called *stiffness forces*. In fact, the stiffness force in a column is the column stiffness times the relative displacement between its ends.

Figure 2: Inertia force and relative motion within a building

Horizontal and Vertical Shaking

Earthquake causes shaking of the ground in all three directions – along the two horizontal directions (*X and Y, say*), and the vertical direction (*Z, say*) (Figure 3). Also, during the earthquake, the ground shakes randomly *back and forth* (- and +) along each of these X, Y and Z directions. All structures are primarily designed to carry the gravity loads, *i.e.*, they are designed for a force equal to the mass M (this includes mass due to own weight and imposed loads) times the acceleration due to gravity g acting in the vertical downward direction (-Z). The downward force Mg is called the *gravity load*. The vertical acceleration during ground shaking either adds to or subtracts from the acceleration due to gravity. Since factors of safety are used in the design of structures to resist the gravity loads, usually most structures tend to be adequate against vertical shaking.

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IITK-BMTPC Earthquake Tip 5

What are the Seismic Effects on Structures? *page 2*

Figure 3: Principal directions of a building

However, horizontal shaking along X and Y directions (both + and – directions of each) remains a concern. Structures designed for gravity loads, in general, may not be able to safely sustain the effects of horizontal earthquake shaking. Hence, it is necessary to ensure adequacy of the structures against horizontal earthquake effects.

Flow of Inertia Forces to Foundations

Under horizontal shaking of the ground, horizontal inertia forces are generated at level of the mass of the structure (usually situated at the floor levels). These lateral inertia forces are transferred by the floor slab to the walls or columns, to the foundations, and finally to the soil system underneath (Figure 4). So, each of these structural elements (floor slabs, walls, columns, and foundations) and the connections between them must be designed to safely transfer these inertia forces through them.

Figure 4: Flow of seismic inertia forces through all structural components.

Walls or columns are the most critical elements in transferring the inertia forces. But, in traditional construction, floor slabs and beams receive more care and attention during design and construction, than walls and columns. Walls are relatively thin and often made of brittle material like masonry. They are poor in carrying horizontal earthquake inertia forces along the direction of their thickness. Failures of masonry walls have been observed in many earthquakes in the past (*e.g.*, Figure 5a). Similarly, poorly designed and constructed reinforced concrete columns can be disastrous. The failure of the ground storey columns resulted in numerous building collapses during the 2001 Bhuj (India) earthquake (Figure 5b).

(a) Partial collapse of stone masonry walls during 1991 Uttarkashi (India) earthquake

(b) Collapse of reinforced concrete columns (and building) during 2001 Bhuj (India) earthquake

Figure 5: Importance of designing walls/columns for horizontal earthquake forces.

Reading Material

Chopra,A.K., (1980), *Dynamics of Structures - A Primer*, EERI Monograph, Earthquake Engineering Research Institute, USA

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Fig. 37 Example of earthquake tips #5: seismic effects on structures (Murty 2005)

(NDMA) was formed. The Disaster Management Act of 2005 (DM Act 2005) was enacted to develop the institutional and coordination mechanisms for effective disaster management. This Act stipulates that a National Plan on Disaster Management shall be prepared in consultation with the State Governments and expert bodies and organizations in the field of disaster management. The Act also stipulates that every Ministry and Department of the Government of India shall make provisions, in its annual plan budgets, for carrying out activities and programmes set out in the disaster management plans. Subsequent to this, the National Disaster Management Authority (NDMA) was set up under the Chairmanship of the Prime Minister.

Several years back the Ministry of Home Affairs, Government of India initiated two programmes for the training of practising architects and engineers (GoI 2004): the National Programme for Capacity-building of Architects in Earthquake Risk Management (NPCBAERM) and the National Programme for Capacity-building of Engineers in Earthquake Risk Management (NPCBEERM). Under the project, 2-5 State Resource Institutes in each State/Union Territory (UT) were identified to conduct training programmes for engineers and architects in the State public works departments, other government organizations and in the private sector. The project also created resource institutes to assist the urban local bodies in the review and revision of the byelaws to incorporate the Bureau of Indian Standard Codes and also to train municipal engineers in earthquake-resistant construction and retrofitting techniques. The goal was to reach 10,000 engineers and 10,000 practicing architects. Eleven national resource institutions were designated, including seven of the Indian Institutes of Technology.

Different State governments have also instituted some capacity-building initiatives. The State Disaster Management Authorities (SDMA) were set up according to the provisions of the DM Act, 2005. Sensitization and awareness building training programmes are part of the mandate of SDMA's and some of these organizations have been quite active.

In addition to government initiatives in capacity-building there are also academic institutions and professional associations as well as NGOs engaged in such activities. Some of these initiatives focus specifically on earthquake risk reduction, such as an earthquake risk reduction programme by GeoHazards Society (GHS) targeted at Aizawl City, capital of the state of Mizoram (GeoHazards Society India 2015). Some focus more broadly on structural engineering issues (including earthquake safety) such as the Structural Engineers Forum of India with its 18,000 members (SEFI 2015), and some even more specifically on earthquake engineering issues, such as the journal, newsletter and annual lecture organized by the Indian Society of Earthquake Technology (ISET 2015). Some organizations focus on improving construction practices more generally, such as through mason training programmes and development of construction guidelines; these include NGOs such as People-in-Centre (People in Centre 2015) and National Centre for Peoples' Action in Disaster Preparedness (NCPDP 2015).

The preceding discussion hopefully gives a flavour of the range of capacity-building initiatives that exist in India, from education and training and continuing education programmes to curriculum development activities, some of which are ongoing while others have been rather short-lived. Some initiatives have had a huge impact while some had limited success despite being conceptualized on a large scale. Capacity-building has to be an ongoing process, with both short and long term targets to achieve sustainable results.

7 Learning from recent events

In the last several decades, after major earthquakes in India, there have been innovative rebuilding programmes developed that try to incorporate mitigation, earthquake preparedness, and improvements in seismically resistant design. Several of the rebuilding efforts have generated innovative changes in these practices as well as some interesting social innovations, although these changes have not always proven to be sustainable from one event to the next. This section reviews some of the basic innovations from several recent events.

7.1 Reconstruction after the deadly Latur, Maharashtra Earthquake, 1993

An earthquake of magnitude 6.2 struck the Marathwada region in the state of Maharashtra on September 30, 1993. 7928 persons died, 16,000 were injured and over one million were left homeless. Sixty-seven villages were completely destroyed, with extensive damage reported in another 1300 villages in the Latur and Osmanabad districts. Eleven other districts suffered heavy damage (Jain et al. 1993). The total property loss was estimated at US$ 333 million. Approximately 90 % of the housing stock in the affected area was constructed of uncoursed random rubble stone masonry (Fig. 38). Eighty-four percent had heavy earthen roofs supported by timber planks and joists. In the most severely affected villages, over 70 percent of the housing stock was destroyed or damaged beyond repair (Nikolic-Brzev et al. 1999).

Fig. 38 Typical destroyed village in 1993 Latur earthquake (photo: S. Brzev)

The high level of damage associated with the earthquake can be attributed to several factors, including:

- Vulnerable housing stock.
- Shallow focus of the earthquake, which caused very intense shaking in a small area.
- Time of the event—(early morning when many people were asleep in vulnerable structures).

Based on historical records, Marathwada was considered an area of very low seismicity; therefore no special seismic design provisions were required for residential buildings. The earthquake was a big surprise and caught government and communities unprepared. Moreover, the earthquake affected area consisted of rural settlements, and the majority of earthquake-damaged dwellings were nonengineered, stone masonry structures (Fig. 39).

With funding support from the national government as well as international donor agencies, particularly the World Bank, the Government of Maharashtra (GoM) carried out a comprehensive rebuilding programme. This was the first large-scale rebuilding programme in India since independence, and some of the lessons learned from this experience have been very valuable. The state government established a Project Management Unit (PMU) to guide all aspects of the Maharashtra Emergency Earthquake Rehabilitation Programme (MEERP), which in addition to a major housing reconstruction component also included improvements to infrastructure, economic rehabilitation, social and community rehabilitation, technical assistance and disaster management.

The GoM developed three different types of assistance to those affected by the earthquake, based on the amount of damage:

- Relocation of 52 completely devastated villages including reconstruction at new sites (category A);
- Reconstruction of houses and basic amenities in another 22 severely damaged villages (category B);
- In-situ Repair, Reconstruction and Strengthening (RRS) in over 2000 affected villages spread over 13 districts in Maharashtra. This was by far the largest component in terms of affecting the most houses–228,500 (category C).

Fig. 39 Typical house construction with stone masonry in Marathwada (photo: S. Brzev)

The GoM prepared Guidelines for Repair, Strengthening and Reconstruction of Houses Damaged in the September 30, 1993 Earthquake in Maharashtra, India (GoM 1994), which provided recommended technologies for the repairs and new construction. To assist in the implementation of this massive rebuilding effort the GoM took several additional steps that included (Vatsa 2001):

- Appointing 700 junior engineers who provided technical assistance in the villages;
- Setting up material depots throughout the entire region;
- Procuring construction material through international competitive bidding;
- Setting up bank accounts for about 200,000 programme beneficiaries;
- Setting up procedures for payment of installments;
- Issuing coupons for release of construction materials;
- Appointing community participation consultants specifically for this component; and
- Appointing communications facilitators (Samvad Sahayak), generally women, at the village level to help villagers understand all the various aspects of the programme.

Under the project, a large number of training programmes for masons were organized. In the period from November 1995 to February 1997, approximately 4000 traditional masons were trained in the two most heavily damaged districts, Latur and Osmanabad (Fig. 40). Most of these trained masons also participated in the Repair, Reconstruction and Strengthening (RRS) programme. As seen in Fig. 41, there was an obvious improvement in the quality of masonry construction in the villages where trained masons were doing construction (Nikolic-Brzev et al. 1999). These trained masons were in demand in the neighboring districts as well, which led to more training programmes for masons. A large number of women masons were also trained and participated in the programme (Vatsa 2001). The Government also ultimately released a manual directed at masons and home owners on earthquake-resistant design and seismic strengthening for rural houses (GoM 1998).

The relocation element of the Maharashtra rebuilding programme became the most visible and the most controversial. However, this component was comparatively a smaller part of the entire programme. The largest was the RRS component, which covered over 200,000 participants in more than 2000 villages spread over 13 districts of the state. Under this category, the GoM provided two different packages of financial assistance based on the

Fig. 40 A mason, in Maharashtra, installing through-stone for retrofitting a masonry house (photo: S. Brzev)

Fig. 41 Engineer, masons and home owners with retrofitted stone masonry home. Through–stones are visible (photo: S. Brzev)

amount of structural damage suffered. Guidelines from the International Association for Earthquake Engineering (IAEE 1986) were used to identify five damage categories. More than one million people participated in this programme, which took on the dimensions of a housing movement (Vatsa 2001).

Beneficiaries in the RSS programme were initially given the option of repairing and strengthening their homes, but this approach did not find acceptance among these beneficiaries (Vatsa 2001). Rather, beneficiaries looked upon this assistance as an opportunity to add to their living space. Stones used in their old houses continued to be a source of fear, and they preferred to use burnt clay bricks for any new construction.

In the social science literature there is growing consensus that relocation is a socio-economically risky process that people generally do not choose voluntarily (Barenstein and Iyengar 2010). However, in Maharashtra villagers did not oppose resettlement. In fact, in the 22 less severely damaged category B villages, the beneficiaries refused housing assistance in situ, demanding to be relocated instead. According to Vatsa (2001),

Fig. 42 A relocated village after the 1993 Latur earthquake (photo: M. Greene)

these earthquake victims had lost faith in their traditional building materials and thus preferred to move to modern and "seismically safe" villages (Fig. 42). There are also some who argue that international NGOs were more interested in building new villages in the relocated sites than in supporting communities to rebuild their own houses (Salazar 2002).

This earthquake happened in an area that was considered non-seismic, and placed in the lowest seismic zone of the Indian code. Hence, there were serious concerns as to the validity of the prevailing seismic zone map and the GoM sponsored the development of a probabilistic earthquake hazard map specifically for the Maharashtra state by experts from Lamont-Doherty Earth Observatory of Columbia University. The study by Lamont-Doherty assumed that all reservoirs could trigger earthquakes, and in preparation of a zone map for Maharashtra considered not only the geologic data and historic seismicity, but also the distribution of reservoirs (Nikolic-Brzev et al. 1999). However, the zone map thus prepared was not seriously discussed for implementation, perhaps because a zone map is conventionally seen for the entire country and not for individual states. Had this exercise covered the entire country, rather than just the state, it might have been far more useful towards improving the seismic zone map of India.

A number of lessons emerged from the implementation of the Maharashtra programme that were relevant for the Bhuj earthquake rehabilitation programme in Gujarat. In particular the discussion on owner-driven versus contractor-managed construction, relocation versus in situ rebuilding and the need for training and new guidelines and codes, drew on experiences from Latur.

7.2 A watershed event: the Bhuj earthquake and its reconstruction

On 26 January 2001, an earthquake of magnitude 7.7 occurred in western India. The epicenter was in the Kutch district of the state of Gujarat and created massive destruction in the western and central parts of the state. This was a watershed event for India and led to numerous initiatives towards earthquake safety (refer to the discussion in Sect. 6 on NPEEE and NICEE, for example). The reconstruction was also influenced by lessons from rebuilding after the Latur, Maharashtra earthquake. Many people, in government, academia and the NGO sectors, who had been involved in Latur also played roles in the Bhuj reconstruction and brought their observations and recommendations to the design of various aspects of the reconstruction programme.

The earthquake was a major urban and rural earthquake, the first earthquake in the country to affect cities and towns (Fig. 43) as well as a vast rural area (Fig. 44). The death toll was estimated at 13,805, with another 167,000 injured. Over 1.1 million homes were damaged or destroyed. Social services were severely impaired, with over 5000 health units and 12,000 schools damaged or destroyed. Twenty-one out of 25 districts in Gujarat were affected. The Kutch district was the most severely affected, with approximately 70 % of its buildings destroyed. Eighty-nine percent of the deaths occurred in this district. The government itself was impacted by the loss of staff, office buildings, and records. The cost of restoring private assets to standards resistant to earthquakes and cyclones was estimated at €1.8 billion, with restoration of public assets estimated at €0.55 billion. Output losses were estimated at between €540–720 million, or 2–3 % of Gujarat's gross state domestic product over the first 3 years after the earthquake (Murty et al. 2005).

The scope and breadth of the reconstruction programme was enormous. Funded with money from the governments of India and Gujarat, as well as from external funds from international agencies, particularly the World Bank and the Asian Development Bank, the reconstruction program addressed housing, infrastructure, livelihoods, capacity-building and disaster mitigation. The government quickly set up the Gujarat State Disaster Management Authority (GSDMA), with direct control over the entire rebuilding program and an explicit mandate to promote long-term disaster mitigation, both during the recovery phase and into the future. Several of the innovations developed or encouraged by GSDMA (some of these were also in place after Latur) included:

Fig. 43 One of the about 130 multi-storey buildings that collapsed in Ahmedabad, more than 200 km from the epicentre (photo: R. Goel)

Fig. 44 Destroyed masonry houses in the village of Maliya (photo: C. V. R. Murty)

- Over 1000 materials banks were established to supply cement and steel at subsidized prices.
- Technical assistance was brought into help in the rebuilding process, and particularly to focus on promoting earthquake-resistant technology, by providing training to almost 29,000 masons and 6200 engineers.
- Supporting the rebuilding of over 200,000 housing units and the repair of another 900,000 units. In most cases owners participated actively in the rebuilding and assisted in the design and construction of their homes (Fig. 45). In 20 % of the cases, a public/private partnership between NGOs and the government was instrumental in rebuilding the housing. Little construction work was done by government agencies themselves.
- A quality control organization was employed—a consortium of two government agencies (National Council for Cement and Building Materials and the Central Building Research Institute) and a university (Indian Institute of Technology, Bombay) (Murty et al. 2005).

Fig. 45 Owner driven housing reconstruction after the 2001 Bhuj earthquake (photo: C. V. R. Murty)

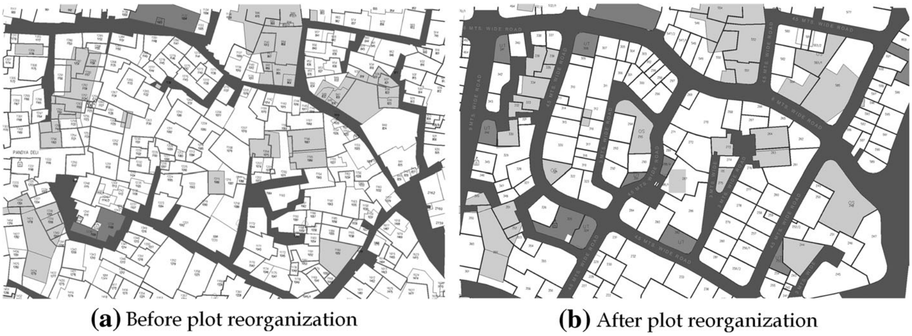

Fig. 46 Development plans for Bhuj city before and after 2001 Bhuj earthquake (*source*: B. R. Balachandran)

Fig. 47 SETU campus in an affected village, with a demonstration house in the foreground. SETUs (meaning "bridge) were set up in various villages to provide NGO staff to work in the communities, acting as liaisons and advocates for affected individuals and families (photo: M. Greene)

- Assistance packages were developed for those who lost their livelihoods.
- Social innovations were advanced, such as setting up bank accounts for direct deposit of housing payments, and requiring that the new houses be registered jointly in the name of both husband and wife.
- Four towns with substantial damage formulated new town and development plans that included adjusting property lines and establishing a more accessible road system shown in Fig. 46 (Tyabji and Balachandran 2003).
- Nongovernmental organizations developed innovative techniques for sharing information with individual owners and tenants (Fig. 47).
- Seismic safety was placed on the national agenda, resulting in new codes and changes in building practices as well as continuing discussions in the social science community on the relationship between earthquake recovery and ongoing development.

While it is not possible to discuss all these innovations in detail, several are highlighted in the following paragraphs; Murty et al. (2005) provide a more comprehensive treatment of the rebuilding effort.

7.2.1 *Rebuilding options*

As with many recent earthquakes, housing was the most seriously affected sector, with close to 215,000 housing units completely destroyed and approximately 928,000 requiring repairs. The government of Gujarat's housing recovery policy focused on developing a participatory, community-driven process, with communities and individual households rebuilding on a self-help basis. Technical support was provided by government, NGOs, and village and local government systems. This major rebuilding component involved a comprehensive set of policies and implementation schemes. The GoG designed the entire reconstruction of the physical assets to be handled through two plans:

7.2.1.1 Owner-driven plan The most widely chosen option for rebuilding housing (about 82 % of those affected chose this option) was the Owner-Driven (OD) plan, where financial assistance was provided directly to owners (in a phased manner) so they could rebuild in situ. Owners could either rebuild their homes themselves or hire contractors and masons with the government assistance package. Figure 48 shows an owner-built home.

7.2.1.2 Public–private partnership plan The government established the Public–Private Partnership (PPP) plan, where NGOs or other private partners would construct private housing (Fig. 49); the government would provide 50 % of the total cost and NGOs the remaining 50 %. NGOs were also encouraged to undertake public infrastructure rebuilding projects, such as schools or health centres, under this PPP program (government and NGO each providing 50 % of the cost). This programme was applicable both to villages that chose relocation (NGOs and government sharing all the costs), and to villages where residents chose to rebuild in situ.

Fig. 48 Owner-rebuilt house in village of Sokhada (photo: C. V. R. Murty)

Fig. 49 Relocated village built by contractor and sponsored by the Government of Maharashtra (photo: M. Greene)

A fairly general consensus has been that the Bhuj rebuilding experience was successful, in part because of the emphasis on the owner-driven reconstruction. The state had to create an "enabling environment" for these owners (Barenstein and Iyengar 2010), which included cash provisions accompanied by the state regulating and/or subsidizing prices of key building materials, strengthening access to good quality construction materials, ensuring support to the most vulnerable, by developing relevant technical guidelines and facilitating technical support and training.

Interestingly, while there was a paradigm shift in the approach of the state government from Maharashtra after the Latur earthquake, to Gujarat, in terms of greater emphasis on the owner-driven approach, it appears that some NGOs were dissatisfied with the GoG approach and they tried to convince communities to adopt the NGO housing design and building technology. While some local NGOs supported self-help construction programmes through additional construction materials, training and technical assistance to communities who opted for financial compensation, most international NGOs proved to be less comfortable with owner-driven reconstruction, and went ahead with the same village adoption and contractor-driven approach they had followed 8 years earlier in Maharashtra (Barenstein and Iyengar 2010).

A survey of overall satisfaction with the quality of housing conducted by a research group in three villages in 2004 (Barenstein and Iyengar 2010) indicated that owner-driven reconstruction, supported by the government and some local NGOs, was the most satisfactory approach. The contractor-driven reconstruction in a relocated site, was the least satisfactory, with only 22.8 % satisfied, and only 3.5 % of people in this group considering the quality of construction to be adequate.

7.2.2 Capacity-building in the reconstruction

Capacity-building was encouraged at several levels and for a variety of stakeholders. One major emphasis in this programme was making the repaired and reconstructed housing earthquake-resistant. In order to do this, technical assistance was provided by assigning government engineers to oversee construction in the various villages (these engineers were also given special training), and by training masons in seismically resistant construction techniques.

In addition to these training programmes, the government developed an educational campaign focused on the need for multi-hazard-resistant reconstruction and retrofitting, as well as on the importance of longer-term disaster management planning. Materials targeted at the general public, such as posters, pamphlets, videos, audiotapes (for radio), and plays, were developed as part of this campaign. Messages regarding disaster-resistant construction were displayed on 600 state transport buses in the five most affected districts. Four special shake table demonstrations were also held as part of this campaign, which illustrated the performance of a small masonry house, with and without bands.

A major emphasis of this rebuilding programme was on mitigation and future disaster preparedness. Significant resources were directed to strengthen the state's disaster management capabilities. This included components of disaster management, seismic engineering, communications, training, information technology, and finance. Providing the legal and institutional framework for this effort was the *Disaster Management Act*, giving the GSDMA authority to oversee disaster management activities, including the development of disaster management plans for all the districts, and the creation of the Gujarat Institute for Disaster Management, which offers a wide range of training programmes. This Disaster Management Act was the first such act established for a state in India and has been a model for other states.

7.3 Tsunami reconstruction

The 26 December, 2004 Indian Ocean Tsunami, triggered by the M9.4 Sumatra earthquake, directly affected 16 nations (Jain et al. 2005). The official death toll in India was in excess of 10,000, with the area adjoining Nagapattinam in the state of Tamil Nadu reporting the highest fatalities. Some 172,000 dwelling units were destroyed in India

Fig. 50 Typical tsunami damage in coastal India (photo: C. V. R. Murty)

(Fig. 50) triggering a huge response, relief and reconstruction initiative, involving the Union and State government, NGOs and other sectors of civil society.

Tamil Nadu's housing reconstruction was entirely contractor-driven, unlike the owner-driven housing reconstruction that had been followed after the 2001 Bhuj earthquake. The state chose to outsource the entire reconstruction as contracts to NGOs. The community's role in decision making during the disaster recovery and rebuilding was minimal. As a result, though the houses built as part of the reconstruction programme were code compliant, the beneficiaries' perception of recovery was low because the new dwellings lacked the comfort conditions of the vernacular systems they were used to for generations (Barenstein and Iyengar 2010). Arguably, the success of post-disaster recovery depends not only on the physical and structural aspects of the housing reconstruction, but also on how the survivors perceive their recovery. Thus, post disaster recovery, rebuilding and reconstruction programmes need to address physical safety, welfare and livelihood issues within a larger framework of cultural preferences, climatic considerations and sustainability.

The Tsunami Reconstruction Programme had one novel innovation in the working of the NGOs through the establishment of a NGO Coordination Centre (Murty et al. 2006). Within a few days of the tsunami event, it transpired that the tsunami-affected areas were not receiving equitable attention from the NGOs, with some areas receiving more attention than others, triggering protests from the survivors. In response, the Government of Tamil Nadu asked three prominent NGOs, experienced in disaster work, and familiar with the local milieu, to set up an NGO Coordination Centre on the premises of the Collector's office in Nagapattinam. The volunteers at the NGO Coordination Centre helped in needs assessment, requisitioning of relief materials and their distribution and the Centre became quite effective in coordinating the relief work. Establishing these types of Coordination Centres during "peace time" can be an effective preparedness tool that provides a mechanism for coordination among groups of NGOs, civil society volunteers and other interested groups before the occurrence of a disaster, for seamless relief work when the disaster actually happens.

7.4 The way forward on learning from earthquakes

Every earthquake disaster (as well as other disasters), even though tragic, brings with it an opportunity to learn from it. This learning can be of two types: (a) lessons in terms of response of the built environment and response of the people, governments, and the society at large, and (b) experience gained in reconstruction. For example, some of the key players in the reconstruction of the Latur earthquake affected area were available to advise and share experiences at the time of the Bhuj earthquake but that may not always be the case. Further, the time window for taking important and critical decisions on rehabilitation of a disaster-affected area is rather short, and it is not always possible to find out adequate information on the experiences from past events. In order to be most useful for decision makers, the lessons from past events need to be readily available. Learning from such events needs to be organized, catalogued and shared in a timely manner, since much of the data is perishable, and the memory of tragic events can be short. With time, distortions in perceptions start to take place. It can be valuable to document lessons to ensure that rebuilding efforts after the next event continue to build on these experiences, not start again. India needs better mechanisms to institutionalize such learning, routinely sharing experiences across governments, disciplines and professions in workshops, journal articles and the web. The academic community across India can play a big role in documenting and analysing such learning.

8 Confined masonry initiative

8.1 The initiative

India has a long history of masonry constructions. The Indus Valley Civilization (3300–1300 BCE), extending from northeast Afghanistan to northwest India, had the first known sewage system consisting of underground drains made from bricks. Some of the masonry techniques in ancient India are difficult to replicate in today's time. The masonry of Ganga Canal (constructed during 1842–1854), for example, is so tough to break that contractors are paid a significantly higher rate for any modifications to this masonry as compared to the masonry works of modern times. Much of the housing all over the country has traditionally been in masonry of different types, depending on locally available materials, and of varying quality. Masonry is strong in compression but can be very weak in tension and hence during earthquake shaking a significant number of deaths have been caused around the world in masonry houses. The reconstruction project in Baluchistan after the 1935 Quetta earthquake (Sect. 3) saw some innovations in masonry constructions to make it more earthquake-resistant. A new type of masonry bond (Quetta bond) was developed wherein vertical voids are left in the brickwork so as to place reinforcement (and the mortar) in the void. This provides the tension capacity to the walls (Fig. 51). The concept of lintel, plinth and roof bands along with vertical reinforcement in corners was also developed. The latter has been adopted in the Indian code IS 4326 for providing earthquake resistance to masonry buildings.

IS 4326 requires certain seismic strengthening provisions in masonry buildings depending on seismic zone and building type. This includes reinforced concrete bands at lintel, roof and plinth levels, corner vertical reinforcement and the like. Two storey buildings in the ITBP Paramilitary Campus in Mahidanda within a few miles of the 1991 Uttarkashi earthquake (M6.4) epicentre had lintel bands and performed well. A single storey house in Killari village had lintel bands even though IS 4326 did not require so in zone I, the zone in which Killari was located at the time of the deadly 1993 Latur earthquake. About one-third the population of Killari village was killed, but this building

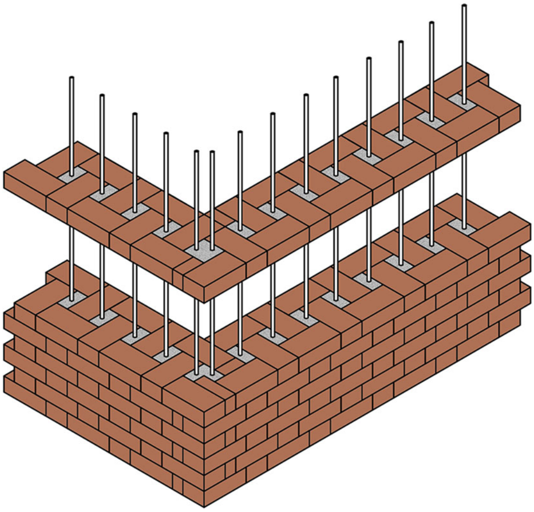

Fig. 51 Pockets (*vertical voids*) receive rebar in Quetta bonds (*courtesy*: K. Mitra)

Fig. 52 House with lintel bands in Killari village near the epicentre of Latur earthquake (photo: author)

Fig. 53 Two-storey masonry house under construction in Bhuj after the 2001 earthquake with strengthening elements of reinforced concrete that exceed IS 4326 requirements (photo: author)

survived the shaking without any damage (Fig. 52). After the 2001 Bhuj earthquake, IS 4326 provisions were used in the reconstruction project with varying levels of conservatism. For instance, some of the reconstructed housing in Bhuj was constructed with strengthening elements that significantly exceeded what was specified by the code (Fig. 53).

The earthquake-resistant features specified by IS 4326 for masonry buildings are often not provided in buildings; instead, one sees a number of three storey residential buildings under construction (even in a place like Delhi in seismic zone IV) with a number of small reinforced concrete columns. The use of masonry and reinforced concrete can be combined into a rational structural system of “confined masonry” which will have far better earthquake performance and the investment on reinforced concrete will not be wasted. Similarly, many three or four storey “reinforced concrete frame” apartment buildings are built in small and medium towns without engineering input and often lack even a proper framing system and load path. Such buildings too can benefit from confined masonry.

Basically, confined masonry buildings can show good seismic performance if provided with two key features: confinement and bond between masonry walls and the reinforced concrete confining elements that enclose these walls. Confined masonry has a proven record of good seismic performance and there has been a serious effort for the last decade in India to introduce confined masonry as a building typology in seismic regions of the country (Rai and Jain 2010). Although traditionally IS 4326 provided some provisions that resemble some of the features of confined masonry, introducing it as a separate technology is a significant improvement over current masonry construction practices.

As discussed above, in 2005, Dr. Svetlana Brzev, a masonry and concrete expert now teaching at the British Columbia Institute of Technology, Canada spent several weeks at IIT Kanpur under the National Programme on Earthquake Engineering Education (NPEEE) and developed a monograph on confined masonry that was published by the NICEE (Brzev 2008). In January 2008 NICEE (with support of EERI and WSSI) organized an international workshop on confined masonry. This workshop and brainstorming session led to the formation of the Confined Masonry Network (http://www.confinedmasonry.org/). A small group from this Network also met in Peru in 2009, and organized introductory sessions on the technology at world earthquake engineering conferences, including the 14th World Conference on Earthquake Engineering in Beijing, China. NICEE also published a monograph on confined masonry for builders authored by Tom Schacher of Switzerland, a member of the Confined Masonry Network (Schacher 2009). A sponsored project from Risk Management Solutions (RMS) and EERI led to the development of international guidelines on the design of low-rise confined masonry buildings (Meli et al. 2011). The Buildings and Materials Technology Promotion Council (BMTPC) in India funded a project at IIT Kanpur to popularize the use of confined masonry. The Indian Institute of Technology Gandhinagar (IITGN) together with IIT Kanpur and BMTPC organized an International Workshop on Confined Masonry in Ahmedabad on April 17–18, 2011. Around 15 invitees from Canada, USA, New Zealand, Peru, and India participated in the deliberations. In February 2014 another small workshop with about twenty people was held on the temporary campus of IITGN, particularly discussing the new campus and following up on earlier strategies to introduce the technology. That workshop included a field visit to the new campus of IITGN where three-storey faculty and staff housing (for about 270 families) and four-storey student hostels (for about 1200 students) were being constructed in confined masonry (Jain et al. 2014). This effort has not only resulted in buildings that should be safer in future earthquakes, but also in a fair amount of cost savings.

About the same time as the new campus construction, a parallel initiative to introduce confined masonry as a technology to masons and home owners throughout rural Gujarat was developed by the Government of Gujarat, with technical support from prominent Indian structural engineers. This initiative is discussed in more detail at the end of this section.

8.2 Confined masonry

The structural components of a confined masonry building are shown in Fig. 54 (Meli et al. 2011): (i) masonry walls—to transfer both lateral and gravity loads from the floor slab to foundation; (ii) horizontal and vertical RC confining elements (tie-beams and tie-columns)—to provide confinement to the masonry panel and to protect it from complete collapse, even during major earthquakes; (iii) RC slabs—to distribute gravity and lateral load to the walls; (iv) Plinth band—to transfer the loads from walls to the foundation

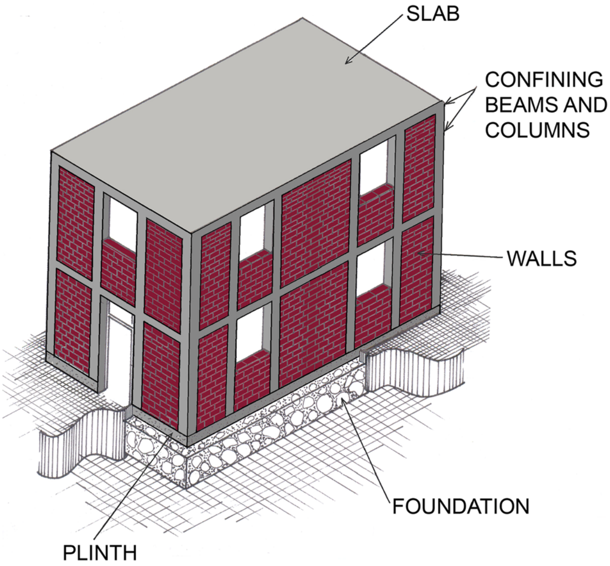

Fig. 54 Components of a confined masonry building (Meli et al. 2011)

system and to reduce differential settlement; and (v) foundation—to transfer the load to the ground. In a confined masonry panel, the masonry wall is constructed first leaving the toothing at either end (Fig. 55). Vertical RC confining elements, also called tie-columns, are then cast. The entire panel height is constructed in several lifts (usually 1 m high). Once the wall construction is completed up to the total storey height, a horizontal RC confining element, also called a tie-beam, is placed atop the wall and is cast monolithically with the floor slab. Additional horizontal RC bands may also be provided at lintel and sill level. The difference in the construction sequence between confined masonry and RC frames with masonry infill walls is important to note. Unlike the infill walls, a confined masonry wall carries the gravity load. Vertical RC confining elements are not expected to sustain the

Fig. 55 Confined masonry under construction at IIT Gandhinagar campus, illustrating the masonry walls and toothing (photo: S. Brzev)

gravity load effects; hence, these elements are smaller in size than RC frame columns. The role of the RC confining elements is i) to enhance the stability and integrity of the masonry wall against the in-plane and out- of-plane seismic excitation, ii) to improve the strength of the masonry wall, and iii) to impart ductility into the seismic response and thereby improve overall seismic behaviour. Reinforcement is provided only in confining elements and the joints in the confining elements are not designed for moment transfer (unlike RC moment frames), thus leading to simple reinforcement detailing.

As a result, good seismic performance can be achieved with low-rise confined masonry without input by qualified engineers, provided that the quality of construction is maintained. Furthermore, confined masonry construction essentially combines two construction typologies, namely, masonry and reinforced concrete, which are prevalent in Indian construction practice. Therefore, workmanship is not expected to be a problem, as construction workers are familiar with the building materials. This is expected to facilitate acceptability in the Indian setting, provided that workers are given training at the initial stage.

8.3 IIT Gandhinagar campus

8.3.1 The project

IIT Gandhinagar (IITGN) is one of the eight new IITs that were established in the academic year 2008–2009. The Institute has been housed temporarily on the premises of the Vishwakarma Government Engineering College in Ahmedabad. In July 2012 the Government of Gujarat gave a piece of land measuring about 161 Hectares (399 Acres) at the Palaj village (Gandhinagar District) to set up the IITGN permanent campus. The site is located in seismic Zone III as per the Indian seismic code (IS 1893 2002), implying a shaking intensity of VII on MSK Scale. For zone III, the Indian code provides peak ground accelerations of 0.16 g at the Maximum Considered Earthquake (MCE) level, and 0.08 g at the Design Basis Earthquake (DBE) level. Therefore, design of the new IITGN campus required attention to seismic considerations.

In Phase I of campus construction, the site will be a fully residential campus for 2400 students and associated faculty and staff. Eventually, the campus will host about 6000 students. In the first instance (Phase 1A), academic buildings, student hostels, faculty and staff residences, and related infrastructure for 1200 students are being constructed. This includes about 45,200 m^2 of plinth area for academic buildings consisting of three- and four-storey RC frame buildings to house the laboratories, classrooms and offices. Three different architectural firms have been engaged to provide comprehensive architectural services for the project. The construction work has been executed by a project team of the Central Public Works Department (CPWD), a department of the Government of India meant to undertake constructions funded by it (Jain et al. 2014).

Students will be housed in both single and double rooms in six four-storey blocks constructed in confined masonry (Figs. 56, 57). In addition, a three-storey dining block has been constructed as a reinforced concrete frame. A total of about 36,000 m^2 of plinth area has been constructed for the hostels.

To house the faculty and staff, a total of 270 apartments are being constructed with a total plinth area of 49,300 m^2. These are grouped in 30 three-storey blocks. Between the blocks are playgrounds, community space and gardens. Housing plans are of three types, namely Type-I (plinth area 108 m^2), Type-II (156 m^2) and Type-III (256 m^2).

The student hostels and apartments were ideal candidates for the adoption of the confined masonry technology. The rooms are of small size (unlike an auditorium or

Fig. 56 Student hostels under construction, Feb 2014 (photo: S. Brzev)

Fig. 57 Same student hostels, nearing completion, Feb 2015 (photo: M. Greene)

classroom), with a sufficiently high wall density. It is unlikely that these buildings will be modified in the future for a different usage by shifting the wall locations. And, the number of storeys is only 3–4. Preliminary indications are that there may be a saving of 10–15 % on the overall cost through the adoption of the confined masonry construction technology over more traditional RC frame construction.

A monograph on this project (Jain et al. 2015) provides details on design of the confined masonry buildings, materials used, and construction of foundations, walls, beams, columns and slabs.

8.3.2 Structural design

EERI guidelines on confined masonry (Meli et al. 2011) were used for structural design in this project with appropriate modifications for seismicity and material properties. The gravity load was assumed to be transferred through the walls only and the contribution of the RC tie-columns in gravity load sharing was ignored. The allowable compressive stress of the wall was computed as per Table 6 with appropriate reductions for the slenderness ratio and eccentricity as per IS 1905.

The lateral load was assumed to be transferred through a set of selected walls and predominantly in shear mode. These walls were well confined by vertical and lateral ties. The EERI guidelines recommend a minimum wall density (the ratio of the wall area in one horizontal plan direction to the floor area of the building) depending on type of masonry units (bricks, blocks, etc.), seismicity and soil conditions. For this project, bricks were considered as solid clay brick, seismicity was assumed as moderate and soil was of a compacted granular type. For this combination, the EERI guidelines recommend a minimum wall density of 1 and 2 % for single- and two-storey buildings, respectively. In line with that, the minimum wall density was selected as 1 % per storey. For example, 3 % wall density was considered for the three-storey apartment buildings and 4 % wall density for the four-storey hostel buildings. When determining the wall density, only well-confined walls were considered. A number of walls with a small effective length or a large opening

Table 6 Recommended design parameters based on test results and considering partial safety factors per IS 1905 (Rai 2013)

Brick masonry type	Prism compressive strength, f_m (MPa)	Basic compressive strength (MPa)	Elastic modulus, E_m (MPa)	Shear strength, v_m (MPa)	Tensile strength, f_m (MPa)
Clay bricks and 1:1:6 mortar	3.89	0.97	250 f_m	Minimum of the following: (a) 0.5 MPa, (b) $0.1 + 0.35\ \sigma$ (c) $0.125\ \sqrt{f_m}$ where σ is overburden pressure due to dead loads	0.05
Clay bricks and 1:4 mortar	3.81	0.95			
Fly ash bricks (Set#1) and 1:1:6 mortar	3.03	0.76	550 f_m		0.07
Fly ash bricks (Set#1) and 1:4 mortar	3.57	0.89			0.05
Fly ash bricks (Set#2) and 1:1:6 mortar	7.63	1.83			0.07
Fly ash bricks (Set#2) and 1:4 mortar	6.82	1.71			0.05

were ignored in the wall density calculations, and therefore were not provided with RC tie-columns.

The base shear associated with a building was calculated per IS 1893 (2002). The importance factor was chosen as 1.0 and the response reduction factor was considered as 2.5. The average shear stress at the ground storey wall was calculated by dividing the base shear by the wall area considered in the wall density calculation. An amplification of 15 % due to torsional effects was also accounted for. The resulting shear stress was compared with the allowable shear stress reported in Table 6. The base shear shared by each confined wall was then distributed vertically per IS 1893 (2002) and the overturning moment at the base was calculated. This overturning moment was assumed to be taken by the tie-columns through axial forces, and the area of concrete was ignored while estimating the axial force capacity of the tie-columns.

Special confining reinforcement was provided at the top and bottom of the vertical ties for one-quarter the storey height. These regions are more prone to shear failure. Minimum shear reinforcement was provided at the middle half of a vertical tie. Similar shear reinforcement was provided in horizontal ties also. The joints of horizontal and tie-columns were not detailed for moment transfer. A lintel band was provided continuously throughout the building. No band was provided at the sill level; instead soffits and jambs of granite stone slab (width 250/600 mm and thickness 18 mm) were provided all around window openings (Jain et al. 2014). Detailing of the joints between tie-beams and tie-columns was simpler than in RC frame construction since these joints do not need to be detailed for moment transfer. Masonry walls did not have any horizontal reinforcement, with the exception of RC lintel bands provided continuously along the wall length above openings (doors and windows). Although the provision of a RC lintel band is not common in confined masonry buildings in countries where this technology has been practised, the team decided to provide lintel bands to comply with the provisions of Indian seismic design standard IS 4326, for load bearing masonry buildings located in Zone III of India.

Considering that this is the first reported large-scale systematic application of confined masonry in India, it is no surprise that the project team faced a number of design challenges. First of all, the architectural and structural team was not familiar with the features of confined masonry buildings in terms of layout and planning. There was a considerable debate whether RC tie-columns require isolated (spread) footings similar to columns in RC frame construction, or if it would be adequate to start the tie-columns at the RC plinth band level (with the provision of adequate anchorage for longitudinal reinforcement). The latter alternative was pursued to expedite the construction process and minimize foundation costs (Jain et al. 2014). For that reason, the RC plinth band (with 400 mm depth) was more robust than in conventional masonry construction practice. Another design challenge was related to areas around staircases that did not meet the wall density requirements. Therefore, these areas were treated as RC frame systems and were isolated from the adjacent confined masonry construction through expansion joints (seismic gaps). Seismic gaps were also used within the buildings with a complex plan shape to create simple rectangular segments in order to minimize torsional effects.

8.3.3 Bricks for construction

Higher compressive strength bricks in large quantity were required to carry the load of the three and four storey buildings, than what locally available bricks could provide. Hence, it was decided to manufacture special Fly Ash Lime Gypsum (FALG) bricks by setting up a manufacturing plant (maximum capacity 65,000 bricks/day) at the construction site. The

Fig. 58 A typical FALG brick (*left*) and a clay brick (photo: S. Brzev)

bulk quantity of fly ash was available from nearby thermal plants. Extensive testing of mechanical and physical properties of the bricks (locally available, and those to be manufactured at site; see Fig. 58) and the resulting masonry was performed at IIT Kanpur (Rai 2013).

With the right composition of materials, it was possible to have FALG bricks with adequate compressive strength. However the FALG bricks also had higher water absorption; this was a concern for below grade masonry applications. Therefore, FALG bricks with the specified compressive strength of 9.0 MPa and maximum 12 % water absorption were used for above grade construction, while foundations below the plinth level were constructed using burnt clay bricks with the minimum compressive strength of 5.0 MPa and maximum 15 % water absorption. These values were obtained as a result of an experimental study performed at IIT Kanpur (Rai 2013). This also helped to expedite the project since larger quantities of bricks could be procured from two different sources, those manufactured on site (FALG bricks) and those purchased locally (burnt clay bricks).The manufacturing process of FALG bricks is illustrated in Fig. 59.

8.3.4 Construction challenges

An interesting issue came up with respect to contract management. The contracts are based on “item rate basis” where the contractor gets paid for the actual volume of work at a pre-decided rate of payment. The Central Public Works Department (CPWD) has detailed specifications on measurements for different items of work. Since confined masonry was not a recognized construction practice in the country at the time of the project, the CPWD specifications did not address the issues that arose in confined masonry. Therefore, a simplistic approach was taken where the potential bidders of the contract were made aware of what could be involved in confined masonry and what additional costs could arise which they needed to build into their bids. They were given details on the extra masonry work involved as well as the necessary formwork, possibilities for delays with the brickwork, construction of tie columns, etc.

8.4 Introducing confined masonry in rural Gujarat

In part as a result of engagement with colleagues around the world in EERI’s Confined Masonry Network and the awareness that confined masonry school construction in China performed better in the 2008 Wenchuan earthquake than RC frame construction, several engineers and architects involved in development activities in Gujarat advocated for the use of this technology in rural housing development plans. A guide was prepared for the Gujarat State Disaster Management Authority (GSDMA), illustrating the construction of a

(a) *FALG brick manufacturing plant* **(b)** *Brick manufacturing machine*

(c) *Brick supply at the plant* **(d)** *FALG bricks at the construction site*

Fig. 59 Manufacturing process for FALG bricks at the IITGN campus construction site (Jain et al. 2015)

confined masonry house (Iyer et al. 2012). As part of the Indira Awas Yojana (IAY) social housing programme supported by the Government of India, the Rural Development Department of the state has embarked on a building programme with an annual target of about 100,000 houses. This programme is aimed at the rural poor, particularly those who are below the poverty level and/or landless. Under this programme, the houses are meant to last 30 years and to be disaster resistant. Thus in the design of the programme various technical options were developed, taking into consideration community lifestyle, geo-climatic aspects, ecology, affordability, and home owners' needs and aspirations. Home owners will be given a choice among six different construction types, including confined masonry. Model houses demonstrating each of the technology options have been developed by the local NGO, People-in-Centre, and have been taken to villages throughout the state to show home owners some of the details of the construction (Fig. 60), as well as options for configuration and size of the houses (Fig. 61). Construction of these houses in this IAY plan is expected to begin in March 2015.

A demonstration construction technology park has been built on the campus of a Gujarat-based NGO, Unnati, in Bhachau, a town in Kutch that was almost completely

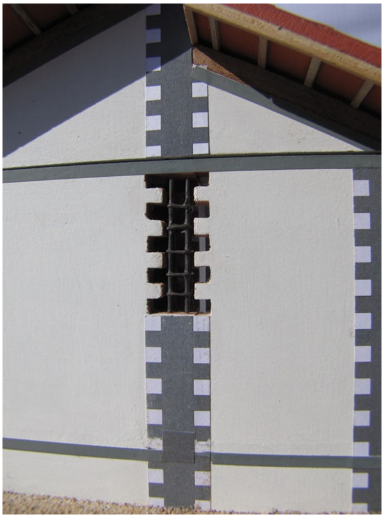

Fig. 60 Model shows some of the principles of confined masonry (photo: V. Rawal)

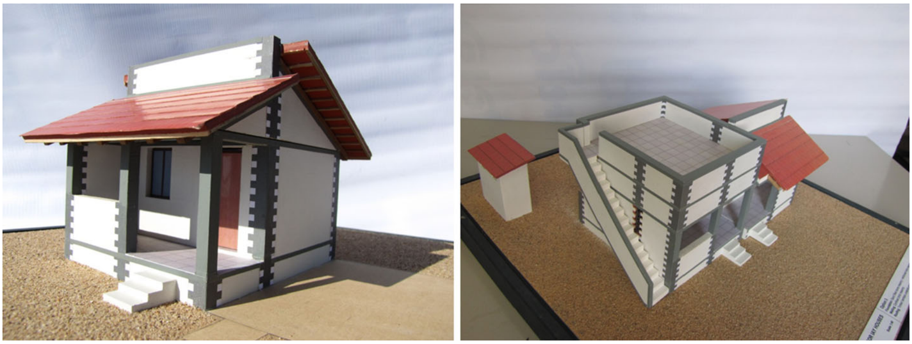

Fig. 61 Models demonstrate options for configuration and size using confined masonry (photo: V. Rawal)

destroyed in the 2001 earthquake. This park includes a well-constructed confined masonry wall in addition to several other technologies appropriate to the region (see Fig. 62).

8.5 Implications

Both of the projects described here are expected to have far-reaching impacts on the construction industry in the country. Hopefully the new campus of IITGN will be seen as a showcase project for a robust and strong construction technology that will be not only safe against earthquakes but also economical. CPWD is a major government construction agency and this is their first major project using confined masonry. It is hoped that their specifications will be modified in due course to include this as an accepted building typology in India. The construction in rural Gujarat will hopefully be seen as a viable alternative to current construction practices in India in view of its simplicity and its seismic performance. It does not require significant engineering inputs and should be ideal for residential apartments of small and moderate size up to 3–4 storeys.

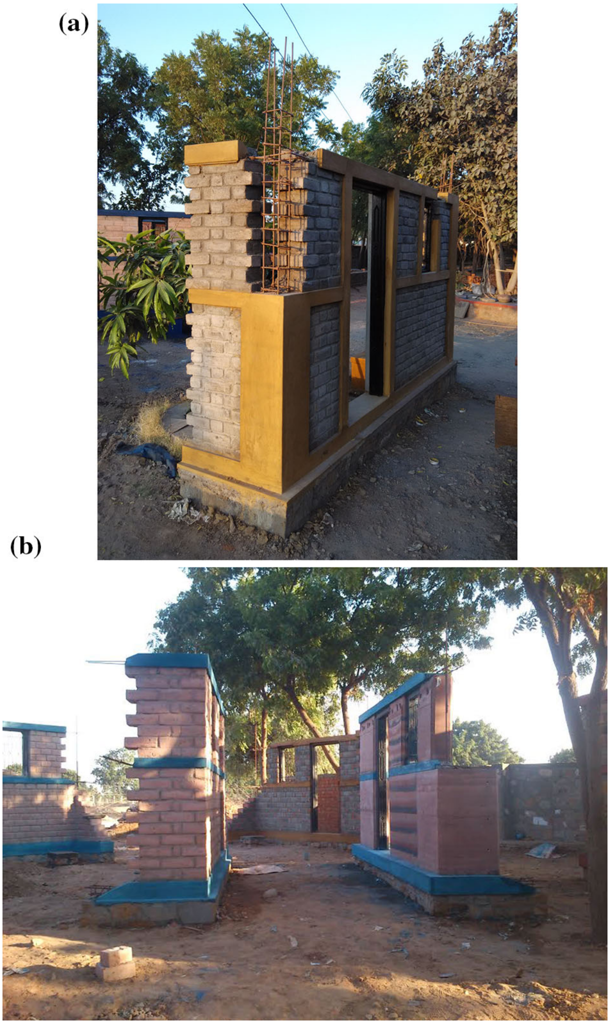

Fig. 62 Demonstration park in Bhachau. **a** A confined masonry wall with critical elements highlighted in *yellow*; **b** Several demonstration walls out of various materials. Plaques explaining the various technologies and correct construction methods will be placed in front of each (photos: V. Rawal)

9 The problem

It can be seen from the earlier discussion that India has a huge stock of unsafe buildings (Fig. 63). In fact, we have a significant number of buildings that are unsafe not just against earthquakes but even under gravity loads as is evident from occasional news stories on the collapse of existing buildings or buildings under construction. According to Sinha and Adarsh (1999), during the period 1984–1995, every year 200–400 major engineered buildings collapsed in Mumbai (most were very old), mainly in the monsoon season. Further, India's geology makes it a site for the periodic occurrence of large and great earthquakes. Together, these two facts indicate a huge earthquake risk for the country; a

Fig. 63 Dense, unregulated reinforced concrete frame construction on slopes in Gangtok city, located in seismic zone IV (photo: C. V. R. Murty)

major earthquake in one of India's booming cities could kill many people and set back development and economic growth by decades. Arya (1992) has estimated the impacts if the 1905 Kangra earthquake of magnitude 8.0 were to happen in 1989. As opposed to 19,000 deaths in 1905, his estimate is that in 1989 the number of deaths could range from 88,000 to 344,000, depending on time of the day and the season in which the earthquake were to occur. These numbers will be significantly higher if the earthquake were to occur in 2015 given the population growth in the intervening 26 years.

Further, in the years ahead, India will have a construction boom in housing and infrastructure that is of a staggering magnitude. With a substantial proportion of our population not having proper housing currently, and with the expected future growth in our population, the country will undertake a huge amount of construction for housing, schools, hospitals, bridges and other infrastructure. Given current construction practices and the lack of an adequate regulatory framework to manage such construction, the seismic risk in the country is growing rapidly.

If India is to achieve its aspirations of rapid growth and improvement in the lives of its people, it must address the problem of seismic risk sooner rather than later. It is not a problem that can be resolved in a few years through the passage of a law or through a stand–alone short–term initiative. It requires sustained attention and tremendous effort on multiple fronts by a diverse set of stakeholders over decades.

To understand this problem, let us break it into several parts:

9.1 Licensing of engineers

Currently in India there is no formal system of competence-based licensing of structural engineers (Jain 2002). Some municipalities may require a minimum level of engineering education from the engineer-of-record, even though a degree does not necessarily ensure competence. In essence, anyone with an engineering degree can practice as a professional engineer and issue construction drawings. In the absence of competence-based licensing of engineers, there are few options for ensuring the competence of a structural designer engaged in a project. There are no requirements for continuing education and there are limited opportunities for a typical engineer to remain up-to-date with technical subjects. Professional licensing serves several purposes: (a) ensuring competence of professionals, (b) enhancing quality and accountability of professionals since the council can withdraw the licence to practise in case of misconduct or incompetence, and (c) increasing the mobility of professionals from one jurisdiction to another.

Unlike many other engineering endeavours, in the case of structural engineering success is not an indication of competence, but failure does indicate incompetence. If an engineering team is able to successfully launch a mission to the moon, their success is a clear endorsement of the team's competence. On the other hand, if a team of architects and engineers is responsible for the design and construction of a building that does not collapse, it does not imply their competence. However, if the building shows structural distress, it is an indication that the team failed to do the job competently.

Further, there are no opportunities to test the structure before its usage. If one were to buy a cell phone that does not work, one could return it to the store. In the case of an apartment, the person living in it can only hope that it has been built to be safe against earthquake, fire and other hazards. Hence, there is a far greater need in the construction industry to ensure the competence of professionals before allowing them to practise independently. Civil engineers have often not been successful in conveying to policy makers in India that licensing is a particularly critical matter for civil engineering (and to some extent electrical and mechanical engineering) as it concerns the safety of the built environment, and that the issue of licensing need not be seen through the same lens for all branches of engineering. Appendix describes the salient features of licensing of engineers in California to give some context on this issue.

India has a licensing system for a number of other professions. The Council of Architecture (CoA) and the Medical Council of India (MCI) ensure that the colleges meet certain standards, and follow certain requirements in their curricula. This forms the basis for these Councils to provide a license to graduates of such colleges. The Institute of Chartered Accountants of India (ICAI) does not oversee curricula in the colleges, but conducts a rigorous written examination to award a license to practice as a Chartered Accountant. Regardless of whether a license is based on the intervention at the level of college education (e.g., MCI and CoA) or based on a competence-based examination (e.g., ICAI), there is the opportunity to enforce professional standards since these councils can withdraw the license to practise in the case of malpractice.

Unfortunately, efforts made in the past towards licensing of engineers have not been successful:

(a) In 2002, a number of professional organizations and institutions of engineers came together to form the Engineering Council of India (ECI). ECI took up the discussions on licensing of engineers, but those discussions have not been successful to date.
(b) In 2006, the Government of Gujarat passed the Gujarat Professional Civil Engineers Act for the creation of the Gujarat Council of Professional Civil Engineers to provide for the registration of professional civil engineers, based on an examination. The Act provided that only a professional civil engineer registered by the Council could certify buildings with more than 140 m^2 of plinth area, buildings more than ground plus first storey, or buildings other than load bearing type masonry structures. The Council was formed in 2010 but no significant progress has been made to date towards the implementation of the intent of the Act.

9.2 Professional competence

India has many great engineers and architects, but in a country of its size with its vast geographic, cultural and educational diversity, there are also many engineers and architects who lack the adequate skills and expertise necessary to practise good structural engineering. For instance, one sees building designs not having an adequate structural load path, columns of unrealistically small size, and indiscriminate perforation of structural beams for drainage or HVAC systems (Fig. 64). Teaching in most engineering schools around the world emphasizes the basic theory, and India is no exception. The engineering curricula are designed with the expectation that upon graduation young engineers will work under the supervision of experienced and competent seniors and in due course will learn to provide good engineering services independently.

In the absence of competence-based licensing, without adequate supervision by competent experienced engineers, and with no additional layers of checking the drawings, an engineering graduate may often design and sign drawings that have fatal errors. The computer tools available for analysis and design of structures have compounded the problem further. Many engineers tend to take the computer program as the ultimate engineer and either do not have the time or the capability to ensure that the design and details coming out of a computer analysis make sense.

There is a huge construction boom in India with an unprecedented number of multi-storey residential buildings coming up in the towns and cities and the urbanizing fringe areas, to meet the urban housing shortage (Fig. 65). Most are reinforced concrete frame structures with unreinforced masonry infill walls and are constructed by property developers who do not have a long-term stake in such buildings. While there are some reputed developers who may not compromise on the quality, many tend to cut corners to save cost of the structure as multi-storey housing is a very cut-throat, competitive process. Government buildings do not normally have the same pressure to save on the cost of the structure, and government engineers will not want to jeopardize their future prospects by doing a poor job. Developers of taller buildings and major commercial structures may not

Fig. 64 Pipes perforating the beam of a reinforced concrete frame near the beam column joint in the city of Kanpur in 2005 (photo: C. K. Jain)

Fig. 65 Multi-storey apartment building under construction in a city in India (photo: author)

focus as much on saving costs on the basic structure and prefer to engage reputable design firms.

Cutting corners on the part of contractors, engineers and architects can contribute to the collapse of a building even under gravity loads, which happens in India from time to time. In one such recent event in Chennai in July 2014, a building under construction collapsed, killing 52 people. The chief minister of the state was quoted as saying, “Although the building that collapsed on Saturday had proper approval, it appears the building did not adhere to the approved plan and it suffered from structural defects” (Stalin 2014). Six people were arrested, including the building’s owners, architects and structural engineers.

9.3 Professional associations

Strong and vibrant professional, trade and industry associations can play a significant role in professionalizing the construction industry, and this is particularly so for the associations of civil/structural engineers. Rather than a lack of professional engineering associations, India has a plethora of them. There are small associations that form in individual cities as well as larger national organizations, often more than one directed at the same stakeholders. Some of the independent professional societies in India are listed below, and the author has been associated with many of these:

- Association of Consulting Civil Engineers (India)
- Consulting Engineers Association of India
- Indian Society of Structural Engineers
- Indian Association of Structural Engineers
- Indian Institution of Bridge Engineers
- Indian National Group of IABSE (International Association for Bridge and Structural Engineering)
- Indian Roads Congress
- Indian Buildings Congress

- Indian Concrete Institute
- Indian Geotechnical Society
- Indian Society of Earthquake Technology
- Institution of Engineers (India)

The problem with having so many associations is that they tend to dilute each other and there is no single coherent voice of the profession. With some of these associations competing against each other for programmes, events and resources, none is able to effectively lead the effort for "professionalizing" engineering and/or the construction process more broadly.

It is interesting to note that the Structural Engineers Forum of India (SEFI), which grew organically out of the e-conferences described earlier, has over 18,000 members who have registered to use its online forum, indicating at least some interest in having a place where issues affecting the profession can be discussed. In some countries, professional associations provide testimony to government bodies and help craft legislation and are seen as the voice of the materials providers (masonry, cement) as well as the voice of the construction professions (architecture, engineers, building inspection, masons, etc.). India needs associations that can play such a strong role consistently and our engineering leaders need to give priority to developing such associations.

9.4 Building code enforcement

In cities and towns, the municipal authorities regulate building construction while there is no regulation for buildings in the rural areas. As urbanization proceeds and rural areas on the outskirts of cities are incorporated within the cities, the rural buildings constructed without regulation become part of the city. Different cities have different requirements for the issuance of building permits and typically require a certificate from an engineer and/or an architect that the building complies with all the codes and is structurally safe. Not many municipalities require even submission of structural drawings, and some may ask that a building of a certain size be proof checked and certified by another engineer. To the best of the knowledge of the author, no city/town in India has a system of getting the structural drawings reviewed internally even randomly. As a result, the safety certificates issued by the engineers/architects "are easy to procure, sometimes on payment of small money, and need not have any correlation with how a building is built" (Jain 2005). It is not uncommon in India for a building to be designed by one set of architects and engineers, and to have another set of architects and engineers sign the drawings/certificates for the purpose of the municipal approvals; the rationale is that the professionals doing the actual work on design find it onerous to do the paper work with the municipality and find it easy to engage someone who is willing to do so at a very nominal cost.

Municipalities in India do have a system of checking the building for fire safety and a building may be denied an occupancy permit if the Fire Department finds that the building does not comply with the fire code. Unfortunately, municipalities do not have a similar system for checking for structural safety for a variety of reasons: (a) the need for enforcement of structural safety has not always been emphasized by professionals to the administrators, (b) there is concern that such enforcement will cause corruption rather than solve the problem of structural safety, and (c) the engineering staffs associated with municipalities lack a structural engineering background and temperament since most often they handle problems of drainage, water supply and unauthorized constructions. Engineers in the building department of a municipality may look at a building's drawings for conformance with issues such as open space requirements and floor area ratio, rather than structural safety. In fact, a large percentage of municipal engineers may be diploma holders (3 years of engineering education after class 10) as opposed to degree holders (4 years of engineering education after class 12).

When municipal authorities seek safety certificates from professionals but as a policy do not verify the design even with random checks, it makes such certificates worthless. One can imagine the consequences if the income tax department were to say that all citizens should pay taxes owed to the government and just attach a certificate from an accountant that this has been done, and that the department as a policy will not examine whether anyone actually paid the taxes.

In many important projects, a client may require the structural drawings to be reviewed and proof checked by another firm; this is effective sometimes but not always. The author is aware of situations where substantial structural distress happened to major structures notwithstanding such peer review. In some cases, the client may require peer review or proof checking by a university professor and this too has a mixed success rate, depending on the quality of attention that the professor concerned gives to the project.

Even when the drawings for the project have been prepared with competence, there is no system at the municipality level to ensure that the same is being faithfully implemented at the site. Correct implementation at the site must be ensured not only by the construction agency and the owner but also by the municipalities through periodic site inspections.

The Nepal Society for Earthquake Technology (NSET), with support from the USAID/OFDA, is currently providing technical support to cities across Nepal to incorporate the building code into the building permit process (NSET 2014). It seems that several municipalities in Nepal have started the process for implementation, and allocated budget for the same. It is reported that Siddharathanagar and Butwal municipalities in Nepal have established separate earthquake safety units to check building code compliance. Indian cities too must undertake this, and huge progress will be made on the road to seismic safety the day our municipalities start effectively checking structural designs. The guidelines prepared by the National Disaster Management Authority for managing earthquakes (NDMA 2007) provide for enforcement of codes in addition to many other elements and it is now time to implement the same.

9.5 Construction typologies

Despite its best efforts, the country will continue to see construction of a large number of housing units without adequate and competent engineering inputs. In this scenario, there is an urgency to develop, test and propagate construction typologies that are inherently safer. If a common man can build a safe home with locally available construction materials and skills, it will solve a huge problem of unsafe constructions in the informal sector. In fact, such typologies are needed not only for the informal sector, as even the formal sector can benefit from these.

Most urban construction in India consists of either masonry load-bearing buildings of up to three or four storeys, or reinforced concrete frame buildings with masonry infills as walls. Their safety can be significantly enhanced by (a) adopting confined masonry construction in the case of masonry load-bearing constructions (Sect. 8), and (b) providing reinforced concrete shear walls in the case of reinforced concrete frame buildings. However, there could be numerous other solutions. As discussed in Sect. 3, the Assam-type housing that emerged as a result of the 1897 Assam earthquake, and the Quetta bond that emerged during the reconstruction after the 1935 earthquake in Quetta both provide excellent resistance to earthquakes and do not require serious engineering efforts.

9.6 Seismic retrofitting of existing buildings

The issue of retrofitting of existing buildings and infrastructure comes up after every disastrous earthquake. In some countries, with systems already in place to ensure that new constructions are safe and code-complaint, retrofitting options are certainly appropriate to consider. In a country like India, however, without a system to ensure the safety of new buildings, retrofitting of existing buildings is not a priority over new buildings. It is not often appreciated that the urgency and highest priority (and resources) must go towards ensuring that no new constructions take place that are unsafe. Let us assume the average life of a building as 50 years, that the building stock in India will grow at 2 % per annum, and that from today onwards no unsafe building will be constructed. In such a scenario, 20 years from now, more than two-thirds of the building stock will be safe and a large part of the problem will be solved even without retrofitting.

Notwithstanding the above argument, there is still a need for the retrofitting of public buildings, important buildings, very unsafe buildings, etc. Some issues that give context to retrofitting in India are listed below:

(a) *Retrofitting can be expensive* Depending on the state of an existing building and the level to which it is planned to be retrofitted, the cost of retrofitting may range from 10 % to 50 % of the cost of a similar new facility (e.g., Spence 2004). It is far cheaper, more effective and simpler to include seismic features in the original construction than to do subsequent retrofitting.

(b) *It requires considerable expertise and technology for retrofitting* It may be relatively straightforward to retrofit a simple and ordinary masonry building against collapse. However, considerable technical (both design and construction) know-how may be needed to retrofit complex structures. For instance, the Department of Transportation in California in the U.S. (Caltrans), had to undertake years of research while executing its retrofitting programme, and it spent about 1 % of its budget on research for retrofitting.

(c) *Retrofitting is a long-haul process* In view of the costs and efforts required, a sensible retrofitting programme will need a timetable running into decades depending on the size of the inventory of unsafe constructions and the resources available for retrofitting. As an example, Caltrans has taken about 35 years to seismically retrofit its bridges at a cost of over $10 billion.

(d) *Important public buildings need priority for retrofitting* In the 2005 Kashmir earthquake, about 19,000 children died in collapsed school buildings (EERI 2006). Since we expect our children to go to school, we must then ensure that the schools are safe. A retrofitting policy and initiative is needed for schools, hospitals and other important public buildings.

(e) *A sensible prioritization system is needed* Since any retrofitting programme will be a long-term project, a prioritization scheme must be developed carefully so as to maximize safety with the amount spent. The scheme should consider seismic hazard at the site, vulnerability and residual life of the building, cost and ease of retrofitting, consequences of failure, etc.

Just as in the case of developing new seismic codes and updating existing codes, considerable work is needed to develop consensus documents on the seismic assessment of existing buildings, prioritization schemes for undertaking retrofitting, and methodologies (with specifications) for seismic retrofitting. In addition, a vigorous research programme is needed focused on existing building typologies in India.

9.7 Sustained training and education

There have been several good initiatives for awareness building, training and education in earthquake engineering. Unfortunately many of these have been one-off, funded for just a few years and they have not been sustained. One example is the National Programme for Earthquake Engineering Education; when initially conceived it was expected to run for 10–20 years but ended up receiving funding for only four. There are some activities related to earthquake engineering at most of the Indian Institutes of Technology, but these are not well coordinated. Individual states have some natural hazards awareness building programmes, but information on these is difficult to obtain. Training for masons also exist, but again is typically organized by individual NGOs and not part of an institutionalized culture of safe building practices. There is little focus on raising awareness generally, among all those involved in the building industry, about the risks posed by unsafe building practices, from no inspection to poor design, to cutting corners with materials, or to using unsafe materials and technologies. There is a clear need for massive and continued (for 10–20 years) programmes to provide training and education on safer constructions to different stakeholders at various levels.

9.8 Research and development

Many technologies are fairly universal, such as those connected with defence, the space programme or automobiles. If India were to choose not to invest in developing such technologies, it has the option to borrow or buy these products from overseas. However, many aspects of earthquake engineering can be quite contextual and it is not always possible to imitate what is happening elsewhere because of different construction practices and skills, building materials, climatic conditions and living habits. Substantial research and development are needed to address such unique problems; only some are listed below just to give a flavour of the issue:

(a) The development of new building typologies and technologies appropriate for Indian conditions and that are inherently good for resisting earthquake shaking. One requirement for such technologies to be effective is that they must not require significant sophistication in design and construction supervision.
(b) Seismic retrofitting technologies appropriate for the existing stock of buildings and infrastructure (e.g. Kaushik et al. 2009).
(c) Large-scale and full-scale verification tests on the technologies so developed; this will require substantial investments in our laboratories.
(d) Research on design issues and on development of codes (and supporting explanatory handbooks) that are appropriate for Indian construction practices and typologies; for instance, reinforced concrete frame buildings with masonry infills (e.g., Kaushik et al. 2006).
(e) Research on seismic design of bridges. Bridges in the deep alluvium of the Indo-Gangetic Plains are most often supported on large ‘well foundations’ (one form of caisson foundations) that are not common outside the Indian subcontinent (e.g., Mondal et al. 2012).

(f) Geotechnical earthquake engineering problems such as site effects.
(g) Research on the seismic hazard, including paleoseismic studies, ground motion characteristics, attenuation relations (e.g., Jain et al. 2000), and development of modern zone maps, etc.
(h) Assessment of the vulnerability of Indian buildings and infrastructure; development of methodologies for building assessment (e.g., Jain et al. 2010a, b).
(i) Risk scenario development: for instance, what is the likely loss scenario for Delhi (or Kolkata or Guwahati) if ground shaking of 10 % probability in 50 years were to occur (e.g., Arya 1992; Sinha and Adarsh 1999).

In order to take up these and other similar research problems, we need to build considerable research infrastructure (e.g., laboratories including shake tables, geotechnical centrifuges, pseudo dynamic test facilities, etc.) and create a strong research culture in our universities. Far too few earthquake engineering articles appear from India in the scholarly journals presently. A comprehensive National Initiative on Research and Development in Earthquake Engineering is needed for the next 20–30 years (Jain 2007). Finally, as we scale up our research, a focused effort must be made for technology transfer to the profession; for this, professionals too must be engaged in developing and managing the research agenda.

9.9 A lack of champions

Countries with a strong emphasis on earthquake risk reduction usually have multiple champions for seismic safety; ranging from a mother concerned about children in an unsafe school to an elected official with a clear understanding of the enormous risk posed by a major earthquake in his or her constituency. India is a vast country, with a huge risk, and yet we have very few such champions for seismic safety. This may be because potential activists perceive greater risks from other day-to-day threats facing the country, or because there is a lack of understanding of how much risk India faces in a future seismic event, particularly a possible mega-earthquake in the Himalaya. When it is only earthquake engineering experts and academics who champion the cause of seismic safety it not only diverts their attention from core academics but also makes for bad optics; they are seen as beneficiaries of seismic safety programmes (e.g., better funding) and with a vested interest.

9.10 Windows of opportunity

Every major disaster provides an excellent opportunity to promote the safety agenda. However, such an opportunity comes with a rather short time window as can be seen in Table 7. Just as in everything else, there is diversity in the mammoth problems and challenges that India must tackle to raise the quality of life for its large population: basic education, healthcare, urban and rural amenities such as water, sewers and transport, road safety, unemployment and poverty, terrorism, and so on. And, it is not always clear if safety in general and seismic safety in particular should get precedence over nourishment or basic education for children. Hence, in India's case, the window of opportunity provided by a disaster tends to be even shorter than what is the case elsewhere. By the time society comes to terms with the immediate aftermath of a seismic disaster, something else takes away its attention.

In some cases, the country has been able to leverage opportunities provided by earthquake disasters and in many instances it has not been able to. When preparatory work has

Table 7 Long term human response to earthquakes (Keys 1988)

Stage	Time	Event	Reaction	
			Positive	Negative
1	0–1 min	Major earthquake		Panic
2	1 min–1 week	Aftershocks	Rescue and survival	Fear
3	1 week–1 month	Diminishing aftershocks	Short term repairs	Allocation of blame–builders, designers, officials etc.
4	1 month–1 year		Long term repairs Action for higher standards	
5	1 year–10 years			Diminishing interest
6	10 years to the next time			Reluctance to meet costs of seismic provisions, research etc. Increasing non-compliance with regulations
7	The next time	Major earthquake	Repeat stages 1–7	

been done ahead of time and a clear road map developed *apriori*, the efforts for implementation within the time window of opportunity have been successful, e.g., NPEEE. On the other hand, if discussions on developing the action plan itself start after the disaster, the attention and the urgency are lost by the time deliberations are over. Hence, champions of safety need to be strategic in their efforts for seismic risk reduction (e.g. Comartin et al. 2004), and use the peacetime to develop strategies and action plans.

With the above view towards leveraging the opportunity a disaster may provide, and offer consistent advice to decision makers who otherwise may receive advice, even conflicting, from many "experts" after a disaster, *"Guiding Principles and Elements for Effective Seismic Safety Programs"* was developed by a group of international experts. These guidelines have been endorsed by the International Association for Earthquake Engineering (IAEE) and the World Seismic Safety Initiative (WSSI). This document owes its origins to an Ad Hoc Experts' Group (32 experts from around the world) on Earthquake Safety in Schools that met in Paris in February 2004 under the aegis of the Organization for Economic Cooperation and Development (OECD) and GeoHazards International (GHI) and developed the "*Guiding principles for mandatory national school seismic safety programmes*" (OECD 2004). These guidelines were further developed and expanded in scope to address not just school safety, but seismic safety at a societal level by a smaller group of experts who met in Beijing, China in February 2006. The resulting Guiding Principles and Elements are meant to be standards for a national seismic safety program with applicability across nations, and cover all issues ranging from awareness and capacity-building, to licensing of professionals and enforcement.

9.11 Earthquake problem versus building problem

The author believes that in a country like India, the solution to the seismic safety problem has been delayed because it is often projected as an 'earthquake problem' rather than as a 'building problem'. A building must provide safety to its occupants against so many hazards, including the earthquake hazard. However, often we place too much emphasis on 'earthquake engineering' and too little on 'building engineering'.

Earthquake engineering has emerged in the last several decades as a strong discipline and has made huge progress. However, in many developing countries, including in India, it has not been integrated into civil engineering and continues to be seen as a super specialty. There is a far better chance of routine structures being earthquake-resistant if earthquake safety is not seen as something additional over and above routine engineering, but becomes an integrated element in routine engineering practice. For instance, when one constructs a house, it is expected that the roof will not leak during the rainy season and the design and the construction engineers concern themselves with ensuring this; no special class of 'rain engineers' need to be called upon to ensure the building does not leak. In a similar way it is sometimes counter-productive to have too much emphasis on 'earthquake engineering' and make it stand apart, instead of having it integrated within civil/structural/geotechnical engineering in a seamless manner.

At times, after disastrous earthquakes, a significant focus has been placed on seismic instrumentation and seismic microzonation in the belief that these are critical for achieving seismic safety, and the opportunities provided by the disaster to push for safer construction have been lost. Policy makers need to be sensitized to the fact that no amount of zonation, microzonation or instrumentation can help until the building constructions improve.

Finally, one cannot achieve earthquake safety if the focus on overall quality (for instance, durability) and safety (for instance, construction safety, safety against fire, against structural distress) in the construction industry is missing. Therefore, instead of talking about 'earthquake engineering,' we must push for improvements in the entire chain of the construction industry. Any interventions in earthquake safety must go together with interventions towards better constructions.

In order to execute a civil project successfully, one must ensure that the entire chain of those involved in the building industry is doing the right thing. Just as a good restaurant must ensure hygiene at all stages of preparation, handling and service of food to guarantee it is not infected with bacteria, so it is in the case of the building industry. All stages of the life cycle of a civil project, conception, design, detailing, construction and commissioning, must be done right for the project to be successful. There are three types of challenges that can be faced in this process as illustrated in Fig. 66:

(a) *Error of intention*: Someone intends not to follow the correct practice for whatever reasons (for instance, to save costs by using less building materials), or someone undertakes execution of the project even when one knows that one is not competent to do so.
(b) *Error of concept*: Due to insufficient knowledge, someone unintentionally does not follow the correct practice (for instance, poor concepts of engineering mechanics), and in many cases the person does not know that he does not know (for instance, a design engineer may not know about some aspects of the engineering problem).
(c) *Error of execution*: Despite best intentions, errors may happen in execution at any stage of design and construction.

To ensure that the construction industry will be, by and large, free of these errors, a fairly sophisticated system for managing the construction delivery is needed and there are no short-cuts to achieve this.

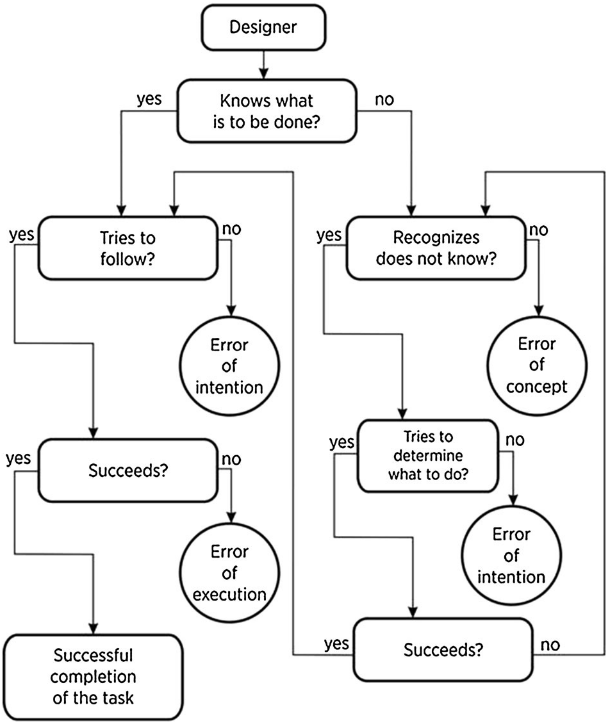

Fig. 66 Alternative paths with regard to acceptable practice (Nowak and Arafah 1994)

10 Concluding remarks

The late Charles Richter wrote (1958), *"It is easy to underestimate India, geographically and otherwise."* India offers tremendous diversity in all aspects: its geography, its geology, its people, its culture, its food, its construction typologies, its engineering capabilities, and its governance system. Almost anything can be said about India and it will be true but the exact opposite of the same statement will also be true. Western visitors, new to India, can be easily confounded by the numerous contradictions in daily life and they may find it not-so-easy to appreciate that almost anything in India can easily fall in between black and white into numerous shades of grey. That so many norms and expectations in the society are implicit, rather than explicit, can be difficult to comprehend for an outsider.

On one extreme, Indian engineers have successfully executed great projects and continue to do so. This ranges from construction of bridges and dams in the most challenging geological and geotechnical settings, sending a highly acclaimed mission to Mars at an extremely low cost, to indigenous design and construction of a 500MWe Prototype Fast Breeder Reactor (PFBR) at Kalpakkam that is expected to be commissioned shortly. And, on the other extreme it is not uncommon to see a poorly designed reinforced concrete building under construction with the names of architectural and structural firms of long standing in title blocks of the "good for construction" drawings. Some great work has been done in the country in seismic reconstruction and rehabilitation in recent years on one hand, and on the other hand we continue to build many unsafe buildings every day, adding to our seismic risk.

The problem of unsafe constructions, at times even in the formal sector under the supervision of architects and engineers, is a rather sophisticated problem that India must solve. It will require a multidisciplinary approach involving engineering, social, political and economic interventions. Research articles, reports, microzonation maps, codes are all meant to improve what gets built on the ground, but do not make any difference if the actual improvement in construction does not take place. Hence, a narrow view of earthquake safety from an ‘earthquake’ viewpoint cannot be effective and the focus must shift from ‘earthquake engineering’ to ‘good building constructions’.

India anticipates unprecedented growth over the next decade, an opportunity both exciting and daunting. The prospects for growth for all those in the construction process are enormous, yet with the possibility of continuing many of the potentially fatal errors discussed above. Foremost among the unfinished agenda to improve this construction process are: (a) competence-based licensing for engineers in general and structural engineers in particular, (b) enforcement of building codes by the municipal authorities, and (c) development and propagation of building typologies that are inherently earthquake-resistant. The emphasis, with particular urgency, should be on new construction of all kinds, from the millions of housing for the masses that the central government has identified as a priority, to the expensive apartment buildings for the affluent.

Clearly, India has come a long way on the road to earthquake safety. And yet, much remains to be done before this journey is completed. Creating a system and culture for building safe houses in 21st century India is something not only possible but an absolute necessity. This is the least that the more than one billion people of India expect from professionals and others associated with the construction industry. Providing such safe housing is both our challenge and our obligation.

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Appendix: licensing of engineers: a perspective from California

Licensing of civil engineers in California started due to the collapse of San Frances Dam in 1929. It was realized that in order to ensure public safety, civil engineering practice must be regulated to ensure adequate competence.[5] In the United States, licensing is managed at

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[5] Based on the author’s visit to the office of *California Board of Professional Engineers and Land Surveyors* in Sacramento, CA, USA in 2003.

state level and each state may have different requirements for granting of an engineering license. California has three types of license:

1. In the case of the Professional Engineer (PE) license in Civil, Electrical and Mechanical Engineering, the law defines which services only a PE can perform. Hence, one must have PE license to perform one of these services.
2. PE in many branches such as Traffic Engineering, Chemical Engineering, Environmental Engineering, etc., only adds a title to the person. A person with PE in Environmental Engineering may find it easier to get more professional work but there are no services that only a PE in Environmental Engineering can perform.
3. A PE in Civil Engineering in California can seek one of the two specialized licenses: Structural Engineer and Geotechnical Engineer. These enable a professional to work on specific activities defined by the law: for instance, one can do structural design of schools and hospitals only if one has Structural Engineering license: for all other structural engineering work, a simple PE in Civil Engineering will do.

The majority of engineering licenses in California (~90 %) are given in civil engineering, with all the remaining branches of engineering constituting only 10 % of total. This is because an engineering license is useful when public safety is to be ensured by preventing shoddy engineering, and there are no other means to ensuring quality of professional work. For instance, an automobile manufacturer will ensure quality of its engineering through success of its products and may not need licensed engineers.

Typically, the PE license is awarded on the basis of very rigorous examinations, covering both breadth and depth of knowledge. In the case of PE in civil engineering, California also requires a separate examination on seismic engineering. These examinations can be quite difficult for some engineers to pass, and many may struggle for more than a decade to be able to make it to the license.

At the beginning of a system for licensing, usually a *Grandfather Clause* is provided that allows professionals already practising for a number of years to continue to practise without having to appear in the examinations. However, such persons must apply within a certain time limit of introduction of licensing. For instance, California started the license of Geotechnical Engineers in 1987 and in 2003 had about one thousand engineers grandfathered in geotechnical engineering.

References

Amateur Seismic Centre (2015) http://www.asc-india.org/ Pune, India. Accessed 3 May 2015

Ambraseys N, Bilham R (2003) Earthquakes in Afghanistan. Seismol Res Lett 74(2):107–123

Arya AS (1992) Possible effects of a major earthquake in Kangra region of Himachal Pradesh. Curr Sci 62(1&2):251–256

ATC (1985) Earthquake damage evaluation data for California. Report ATC-13, Applied Technology Council, Redwood City, CA

Baird-Smith R (1843) Memoir on Indian earthquakes. J Asiat Soc Bengal 12(II):1029–1056

Bapat A, Kulkarni RC, Guha SK (1983) Catalogue of earthquakes in India and neighbourhood. Indian Soc Earthq Technol, Roorkee

Barenstein JD, Iyengar S (2010) India: From a culture of housing to a philosophy of reconstruction. In: Lyons M, Schilderman T, Boano C (eds) Building back better. Delivering people-centred housing reconstruction at scale. Practical Action Publishing, Warwickshire, pp 163–188

Bilham R, Gaur VK, Molnar P (2001) Himalayan seismic hazard. Science 293:1442–1444

BMTPC (2006) Vulnerability atlas of India. Building materials and technology promotion council, Ministry of Urban Development, Government of India, N. Delhi

Brzev S (2008) Earthquake-resistant confined masonry construction. National Information Centre of Earthquake Engineering: Indian Institute of Technology Kanpur, India (2nd edition 2011). www.nicee.org

CAI (1965) Earthquake resisting buildings: requirements and design procedure for concrete construction. The Concrete Association of India, Bombay

Census of India (2011) http://www.censusindia.gov.in/2011census/hlo/Data_sheet/India/Housing_Stocks.pdf. Accessed 12 Feb 2015

Charleson AW (1997) Seismic design within architectural education. Bull New Zealand Natl Soc Earthq Eng 30:46–50

Cloud WK, Hudson DE (1961) A simplified instrument for recording strong motion earthquakes. Bull Seismol Soc Am 51:159–174

Hudson DE Interview by Shirley K. Cohen (1997) Pasadena, California, November 12, December 10 and 17, 1997. Oral History Project, California Institute of Technology Archives. http://resolver.caltech.edu/CaltechOH:OH_Hudson_D. Accessed 12 Feb 2015

Comartin C, Brzev S, Naeim F, Greene M, Blondet M, Cheery S, D'Ayala D, Farsi M, Jain SK, Pantelic J, Samant L, Sassu M (2004) A challenge to earthquake engineering professionals. Opinion Paper Earthq Spectra 20(4):1049–1056

Confined Masonry Network (2015) http://www.confinedmasonry.org/. Accessed 3 May 2015

Davis WM (1883) The Cachar earthquake of 1869. Science 1(3):67

Degenkolb HJ (1977) Seismic design: structural concepts, summer seismic institute for architectural faculty. AIA Research Corporation, Washington, DC

EERI (2006) The Kashmir earthquake of October 8, 2005: Impacts in Pakistan. EERI Special Earthquake Report—February. Earthquake Engineering Research Institute: Oakland, CA https://www.eeri.org/lfe/pdf/kashmir_eeri_2nd_report.pdf, Accessed 23 Feb 2015

Geohazards Society India (2015) Design and implementation of an earthquake risk management program in Aizawl City. http://www.geohaz.in/pages/projects/. Accessed 22 Feb 2015

GoI (1940) Earthquake resistant design of low buildings. Government of India Press, New Delhi

GoI (2004) National Programme for Capacity Building of Engineers and Architects in Earthquake Risk Management, Government of India, Ministry of Home Affairs, New Delhi. http://nidm.gov.in/NPCBERM/home.asp. Accessed 3 May 2015

GoI (2011a) Census of India: houselisting and housing census data highlights. Government of India, Ministry of Home Affairs, Office of the Registrar General and Census Commissioner http://www.censusindia.gov.in/2011census/hlo/hlo_highlights.html. Accessed 23 Feb 2015

GoI (2011b) Working group on rural housing for XII five year plan. Government of India, Ministry of Rural Development, New Delhi. http://planningcommission.nic.in/aboutus/committee/wrkgrp12/rd/wgrep_iay.pdf

GoI (2012) Report of technical group on urban housing shortage, Government of India, Ministry of Housing and Urban Poverty Alleviation, National Buildings Organisation, www.mhupa.gov.in

GOI (2015) Union Budget of India, Ministry of Finance. http://indiabudget.nic.in/budget.asp/last. Accessed 10 March 2015

GoM (1994) The guidelines for repair, strengthening and reconstruction of houses damaged in the September 30, 1993 Earthquake in Maharashtra, India. Government of Maharashtra: Bombay, India

GoM (1998) Manual on earthquake-resistant construction and seismic strengthening of non-engineered buildings in rural areas of Maharashtra. Government of Maharashtra: Bombay, India

GSI (1939) Officers of the Geological Survey of India, and Roy S. C., The Bihar–Nepal Earthquake of 1934, Memoirs of the Geological Survey of India, vol. 73

GSI (2000) Seismotectonic atlas of India and its environs. Geological Survey of India, Calcutta

Hicyilmaz K, Bothara J, Stephenson M (2010) Dhajji Dewari construction type in Pakistan and India, EERI and IAEE world housing encyclopedia. http://db.world-housing.net/building/146. Accessed 12 Feb 2015

Housner GW, Interview by Rachel Prud'homme (2015) Pasadena, California, July 2, 3 and 11, 1984. Oral History Project, California Institute of Technology Archives. http://resolver.caltech.edu/CaltechOH:OH_Housner_G. Accessed 12 Feb 2015

IAEE (1986) Guidelines for earthquake resistant non-engineered construction, international association for earthquake engineering, Tokyo, Japan. http://www.nicee.org/IAEE_English.php. Accessed 27 Feb 2015

ICJ (1934) Special issue on the great Indian earthquake. Indian Concr J 8(10):263–324

ICJ(1956a) Design of earthquake-resistant buildings—1. Indian Concr J

ICJ (1956b) Design of earthquake-resistant buildings—2. Indian Concr J

IRC (1946) Standard specifications and code of practice for road bridges (Section II). The Indian Roads Congress, New Delhi

IRC: 112–2011. Code of practice for concrete road bridges, Indian Roads Congress, New Delhi

IRC: 6–2014. Standard specifications and code of practice of road bridges, Section II, Loads and Stresses, Indian Roads Congress, New Delhi

IS 13827–1993. Indian standard guidelines for improving earthquake resistance of earthen buildings, Bureau of Indian Standards, N Delhi, India

IS 13828–1993. Indian standard guidelines for improving earthquake resistance of low strength masonry buildings, Bureau of Indian Standards, N Delhi, India

IS 13920–1993. Indian standard code of practice for ductile detailing of reinforced concrete structures subjected to seismic forces, Bureau of Indian Standards, N Delhi, India

IS 13935–2009. Indian standard guidelines for seismic evaluation, repair and seismic strengthening of buildings, Bureau of Indian Standards, New Delhi, India

IS 15988–2013. Indian standard guidelines for seismic evaluation and strengthening of existing reinforced concrete building, Bureau of Indian Standards

IS 1893: 1962. Recommendations for Earthquake Resistant Design of Structures, Bureau of Indian Standards, N Delhi, India

IS 1893: Part 1–2009. Indian standard criteria for earthquake resistant design of structures—part 1: General Provisions and Buildings, Bureau of Indian Standards, N Delhi, India

IS 1893: Part 2–2014. Indian standard criteria for earthquake resistant design of structurespart 2 Liquid Retaining Tanks, Bureau of Indian Standards, N Delhi, India

IS 1893: Part 3–2014. Indian Standard Criteria for Earthquake Resistant Design of Structures Part 3 Bridges and Retaining Walls, Bureau of Indian Standards, N Delhi, India

IS 1893: Part 4–2005. Indian standard criteria for earthquake resistant design of structure: Part 4 Industrial structures including stack-like structures), Bureau of Indian Standards, N Delhi, India

IS 4967–1968. Indian standard recommendations for seismic instrumentation for river valley projects. Bureau of Indian Standards, N Delhi, India

IS 4326–2013. Indian standard code of practice for earthquake resistant design and construction of buildings, Bureau of Indian Standards, N Delhi, India

ISET (2015) Indian society of earthquake technology. http://iset.org.in/. Accessed 19 Feb 2015

Iyengar RN (1999) Earthquakes in ancient India. Curr Sci 77(6):827–829

Iyengar RN, Sharma D, Siddiqui JM (1999) Earthquake history of India in medieval times. J Hist Sci 34:181–238

Iyer K, Kulkarni SM, Subramaniam S, Murty CVR, Goswami R, Vijayanarayanan AR (2012) Build a safe house with confined masonry. Gujarat State Disaster Management Authority, Government of Gujarat, Gandhinagar, India

Jain SK (2002) Codes, licensing, and education. Earthq Spectra 18(S1):319–339

Jain SK (2005) The Indian earthquake problem. Curr Sci 89(9):464–1466

Jain SK (2006) Implications of the 2004 great sumatra earthquake and tsunami for risk reduction in India. In: Proceedings of the 8th US National Conference on Earthquake Engineering, San Francisco, USA

Jain SK (2007) Need for a National initiative on research and development in earthquake engineering. Curr Sci 92(8):1045–1046

Jain SK (2008) Historical developments in India towards seismic safety and lessons for future. In: Proceedings of the 14th world conference on earthquake engineering. Beijing, China

Jain SK (2010) Some recent capacity building activities in India towards Seismic Risk Reduction. In: Proceedings of the 9th US National and 10th Canadian Conference on Earthquake Engineering.CD-ROM. Paper No. 1677. Toronto, Canada, 25–29 July

Jain SK, Agrawal P (2004) Earthquake engineering capacity building in educational sector in India. In: Proceedings of the 13th world conference on earthquake engineering. Vancouver, Canada

Jain SK, Jaiswal OR (2007) IITK-GSDMA guidelines for seismic design of liquid storage tanks. National Information Centre of Earthquake Engineering, Kanpur

Jain SK, Murty CVR (1998) A state-of-the-art review on seismic design of bridges—part I: historical development and AASHTO Code. Ind Concr J 72(2):79–86

Jain SK, Murty CVR (2003) Some innovative education and outreach projects in India for earthquake risk reduction. Seismol Res Lett 74(5):545–551

Jain SK, Nigam NC (2000) Historical developments and current status of earthquake engineering in India. In: Proceedings of 12th world conference on earthquake engineering, Auckland, New Zealand, Paper, No. 1792, pp 1–8

Jain SK, Murty CVR, Chandak N, Seeber L, Jain NK (1993) The September 29, 1993, M6.4 Killari, Maharashtra Earthquake in Central India, EERI Special Earthquake Report, EERI Newsletter, vol 28

Jain SK, Roshan AD, Arlekar JN, Basu PC (2000) Empirical attenuation relationships for the himalayan earthquakes based on indian strong motion data. In: Proceedings of the sixth international conference on seismic zonation, Palm Springs riviera Resort, California, USA, November 2000

Jain SK, Sheth AR, Bose A (2004) Earthquake engineering in architecture education. J Indian Inst Architects 69(5):29–33

Jain SK, Murty CVR, Rai DC, Malik J, Sheth A, Jaiswal A (2005) Effects of M9 Sumatra earthquake and tsunami of 26 December 2004. Curr Sci 88(3):357–359

Jain SK, Mitra K, Kumar M, Shah M (2010a) A proposed rapid visual screening procedure for seismic evaluation of RC Frame Buildings in India. Earthq Spectra 26(3):709–729

Jain SK, Rai DC, Jaiswal OR (2010b) IITK-RDSO guidelines on seismic design of railway bridges. National Information Centre of Earthquake Engineering, Kanpur

Jain SK, Roshan AD, Yadav S, Srivastava S, Basu PC (2012) Strong motion data from structural response recorders in Indian earthquakes. Earthq Spectra 28(1):77–103

Jain SK, Basu D, Ghosh I, Rai DC, Brzev S, Bhargava LK (2014) Application of confined masonry in a major project in India, Tenth U.S. National conference on earthquake engineering frontiers of earthquake engineering, 2014 Anchorage

Jain SK, Brzev S, Bhargava LK, Basu D, Ghosh I, Rai DC, Ghaisas KV (2015) Confined masonry for residential construction, campus on the Sabarmati monograph. Indian Institute of Technology Gandhinagar

Kaushik HB, Rai DC, Jain SK (2006) Code approaches to seismic design of masonry infilled reinforced concrete frames: a state-of-the-art review. Earthq Spectra 22(4):961–983

Kaushik HB, Rai DC, Jain SK (2009) Effectiveness of some strengthening options for masonry-infilled RC frames with open first-storey. Struct Eng 135(8):925–937

Keys D (1988) Earthquake design practice for buildings. Thomas Telford, London

Kovach RL, Grijalva K, Nur A (2010) Earthquakes and civilizations of the Indus valley: a challenge for archaeoseismology. Ancient earthquakes (Sintubin et al. editors), Geological Society of America Special Paper, vol. 471, 119–127

Krishna J (1959) Seismic zoning of India. In: Proceedings of Earthquake Engineering Seminar, Roorkee, pp 32–38

Krishna J, Chandrasekaran AR (1965) Structural response recorders. In: Proceedings of the 3rd world conference on earthquake engineering, Auckland and Wellington, New Zealand, Vol III, pp 143–150

Kumar SL (1933) Theory of earthquake resisting design with a note on earthquake resisting construction in Baluchistan. Punjab Engineering Congress

Macmurdo J (1824) Papers relating to the earthquake which occurred in India in 1819. Philos Mag J 63(1824):105–177

Mair MC (1942) Structural suggestions for repairs to the quake-proof buildings damaged by the quetta earthquake of 29th September 1941 with the seismic data and structural lessons, Indian Concrete J, July, pp 271–280

Make India (2015) Statistics. makeindia.com/sector/construction. Accessed 25 Feb 2015

Manchester Geographical Society (2013) Journal (vol. 12). Forgotten Books, London (Original work published pre-1945, year unknown), pp 569–570

Medhekar MS, Jain SK (1993) Seismic behaviour, design, and detailing of R.C. Shear Walls, Part II: design and detailing. Ind Concr J 67(8):451–457

Medhekar MS, Jain SK, Arya AS (1992) Proposed draft for IS:4326 on ductile detailing of reinforced concrete structures. Bull Indian Soc Earthq Technol 29(3):15–35

Meli R, Brzev S, Astroza M, Boen T, Crisafulli F, Dai J, Farsi M, Hart T, Mebarki A, Moghadam AS, Quiun D, Tomazevic M, Yamin L (2011) Seismic design guide for low-rise confined masonry buildings. Earthquake Engineering Research Institute and International Association for Earthquake Engineering, Oakland

Mital KV (2008) History of Roorkee University (1949-96). Indian Institute of Technology Roorkee, India

Mithal R, Srivastava S (1959) Geotectonic position and earthquakes of Ganga-Brahmaputra region. First symposium on earthquake engineering. University of Roorkee, India

Mitra K, Ailawadi S, Rai DC (2013) Initiatives in educating future architects in earthquake resistant design practices. Seismol Res Lett 84(5):820–828

Mondal G, Prashant A, Jain SK (2012) Simplified seismic analysis of soil-well-pier system for bridges. Soil Dyn Earthq Eng 32:42–55

Murty CVR (2005) Earthquake tips: learning earthquake design and construction. Department of Civil Engineering Indian Institute of Technology Kanpur and Building Material and Technology Promotion Council, Ministry of Urban Development and Poverty Alleviation, Government of India, New Delhi. Available from http://www.nicee.org/EQTips.php

Murty CVR, Charleson A (2006) Earthquake design concepts. Prepared under the national programme on earthquake engineering education. NICEE: IIT Kanpur

Murty CVR, Jain SK (1995) A proposed draft for IS:1893 provisions on seismic design of buildings; Part I: code. J Struct Eng 22(1):21–29

Murty CVR, Jain SK (1997) Seismic performance of bridges in India during past earthquakes. Bridge Struct Eng 27(4):45–79

Murty CVR, Jain SK (2000) A proposed draft for Indian code provisions on seismic design of bridges—part I: code. J Struct Eng 26(4):223–234

Murty CVR, Sinha R, Jain SK (1998) A report on earthquake resistant construction in civil engineering curriculum. Newsletter of the Indian Society of Earthquake Technology, pp 1–10

Murty CVR, Rai DC, Sinha R, Jain SK (1999) Workshop on developing earthquake engineering industry in India: opportunities & challenges, special report. Ind Concr J 73(8):481–487

Murty CVR, Rai DC, Gupta A, Jain SK (2004) Introducing earthquake engineering in civil engineering curriculum. Ind Concr J 78(2):110–116

Murty CVR, Greene M, Jain SK, Prasad NP, Mehta VV (2005) Earthquake rebuilding in Gujarat, India. An EERI recovery reconnaissance report. February. Oakland, CA: Earthquake Engineering Research Institute 2005-02

Murty CVR, Jain SK, Sheth AR, Jaiswal A, Dash SR (2006) Response and recovery in India after the December 2004 great Sumatra earthquake and Indian Ocean Tsunami. Earthq Spectra 22(S3):S731–S758

NCPDP (2015) National Centre for Peoples' Action in Disaster Preparednesshttp://www.ncpdpindia.org/. Accessed 16 Feb 2015

NDMA (2007) Management of earthquakes. National Disaster Management Authority, Government of India, New Delhi. Available from: http://www.ndma.gov.in/images/guidelines/earthquakes.pdf

Nikolic-Brzev S, Greene M, Krimgold F, Seeber L (1999) Lessons learned over time, innovative earthquake recovery in India. Earthquake Engineering Research Institute, Oakland

Nowak AS, Arafah A (1994) Human error in structural engineering. In Risk analysis. Proceedings of a symposium, August 11–12, University of Michigan, Ann Arbor, USA, pp 165–173

NSET (2014) Safer society: NSET report 2014. National Society for Earthquake Technology-Nepal, Kathmandu

OECD (2004) Taking an initial step towards improving earthquake safety in schools: ad hoc Experts' Group Report on Earthquake Safety in Schools. In Keeping schools safe in earthquakes, organization of economic co-operation and development, Paris (reprinted by National Information Centre of Earthquake Engineering, Indian Institute of Technology Kanpur, India, in 2006), pp 229–237

Oldham T (1883) A catalogue of Indian earthquakes from the earliest time to the end of A.D. 1869, Memoirs of the Geological Survey of India, 29, 163–215

Oldham RD (1899). Report on the great earthquake of 12th June 1897. Memoirs of the Geological Survey of India, vol 29, pp 1–379

Parthasarathy R (2003) A.N. Khosla (1892–1984): irrigation engineer, visionary. The Hindu. Retrieved fromwww.thehindu.com. Accessed 30 Apr 2015

People-in-Centre Consulting (2015) http://www.peopleincentre.org. Accessed 16 Feb 2015

Quittmeyer RC, Jacob K (1979) Historical and modern seismicity of Pakistan, Afghanistan, Northwestern India, and Southeastern Iran. Bull Seismol Soc Am 69:773–823

Rai DC (2005) IITK-GSDMA guidelines for seismic evaluation and strengthening of existing buildings. National Information Centre of Earthquake Engineering, Kanpur, India August http://www.iitk.ac.in/nicee/IITK-GSDMA/EQ06.pdf

Rai DC (2013) Report on evaluation of brick masonry design parameters for IITGN buildings, Department of Civil Engineering, Indian Institute of Technology Kanpur, India

Rai DC, Jain SK (2010) NICEE's role in promoting confined masonry as an appropriate technology for building construction in India. In: Proceedings of the ninth U.S. national and tenth canadian conference on earthquake engineering. Paper No. 1689: Toronto, Canada

Rai DC, Murty CVR (2006) Effects of the 2005 Muzaffarabad (Kashmir) earthquake on built environment. Curr Sci 90(8):1066–1070

Rai DC, Sheth A (2002) Special report—E-conference on Indian Seismic Codes. Indian Concr J 76(6):376–378

Rao MBR (eds) (1953) A compilation of papers on the Assam earthquake of August 15, 1950. The Central Board of Geophysics, Government of India, New Delhi

RDSO (2015) RDSO guidelines on seismic design of railway bridges. bridge & structures directorate, Research Designs and Standards Organization, Lucknow—226011

Richter CF (1958) Elementary seismology. W.H. Freeman & Co., Inc., San Francisco

Robertson RG (1948) Earthquake-resistant structures: the seismic factor and the use of reinforced brickwork in quetta civil reconstruction. J Inst Civil Eng 3:171–184

Salazar A (2002) Normal life after disasters? 8 years of housing lessons, from Marathwada to Gujarat: a response to KS Vatsa. http://www.radixonline.org/gujarat6.htm. Accessed 15 Feb 2015

Schacher T (2009) Confined masonry for one and two storey buildings in low-tech environments—a guidebook for technicians and artisans, National Information Centre of Earthquake Engineering, Kanpur, India (www.nicee.org)

SEFI (2015) Structural engineering forum of India http://www.sefindia.org/. Accessed 18 Feb 2015

Singh U (2009a) A history of ancient and early medieval India. Dorling Kindersley (India) Pvt. Ltd

Singh RK (2009b) Probabilistic seismic Hazard and risk analysis: a case study for Ahmedabad City. Masters' thesis, Department of Civil Engineering, Indian Institute of Technology, Kanpur

Sinha R, Adarsh N (1999) A postulated earthquake damage Scenario for Mumbai. ISET J Earthq Technol 36(2):169–183

Spence R (2004) Strengthening school buildings to resist earthquakes: progress in European countries. In: Keeping schools safe in earthquakes, organization for economic co-operation and development, Paris, pp 217–228

Stalin JSD (2014) After chennai building collapse, civic officials Rush to Inspect Under-Construction Structures" NDTV, July 3rd. http://www.ndtv.com/chennai-news/after-chennai-building-collapse-civic-officials-rush-to-inspect-under-construction-structures-583341. Accessed 19 Feb 2015

The Hindu (2015) Full text of budget 2015–2016 Speech. February 28th. http://www.thehindu.com/news/resources/full-text-of-budget-201516-speech/article6945026.ece. Accessed 10 Mar 2015

Thomson ROC (1940) Earthquake reconstruction on Quetta (Railway) Division 1936-40. Technical Paper no. 307, Railway Board, Delhi

Tyabji A, Balachandran BR (2003) The reconstruction of Bhuj: a case study in the integration of disaster management into planning, and financing urban infrastructure after an earthquake. In: Proceedings of Asian regional conference on urban infrastructure financing and disaster mitigation, Sri Lanka, 14–15 March 2003, USAID/India and USAID Office of Aid Programs

United Nations (2014) Department of Economic and Social Affairs, Population Division

University of Roorkee (1988) Performance of strong motion instruments in the Bihar–Nepal Earthquake of August 21, 1988, Report No. EQ: 88-16, Department of Earthquake Engineering, Indian Institute of Technology, Roorkee, India

Valdiya KS (1998) Dynamic himalaya. Universities Press, Hyderabad, p 178

Valdiya KS (2010) The making of India: geodynamic evolution. Macmillan Publishers India, Delhi, p 816

Vatsa K (2001) Rhetoric and reality of post-disaster rehabilitation after the Latur Earthquake of 1993: a rejoinder, in Radix: The Gujarat Earthquake, http://www.radixonline.org/gujarat5.htm. Accessed 12 Feb 2015

Wesnousky SG, Kumar S, Mohindra R, Thakur VC (1999) Holocene slip rate of the himalayan frontal thrust of India, observations near Dehra Dun. Tectonophysics 18:967–976

West WD (1937) Earthquakes in India. Presidential address. In: Proceedings of the Indian science congress, Hyderabad, pp 189–227