Learning from Earthquakes

Preliminary Observations on the Origin and Effects of the January 26, 2001 Bhuj (Gujarat, India) Earthquake

Several days after the Bhuj earthquake, EERI deployed a team of engineers, earth scientists and an emergency manager to document the tectonic setting; local geological and geotechnical effects; performance of buildings, lifelines and other facilities; and the governmental response to the earthquake. The team was led jointly by Dr. Sudhir K. Jain of the Indian Institute of Technology, Kanpur (IITK) and Dr. William R. Lettis of William Lettis & Associates, Inc., Walnut Creek, CA. The reconnaissance team and the publication of this report were supported by EERI's Learning from Earthquakes Project, funded by the National Science Foundation through Grant # CMS-0001718.

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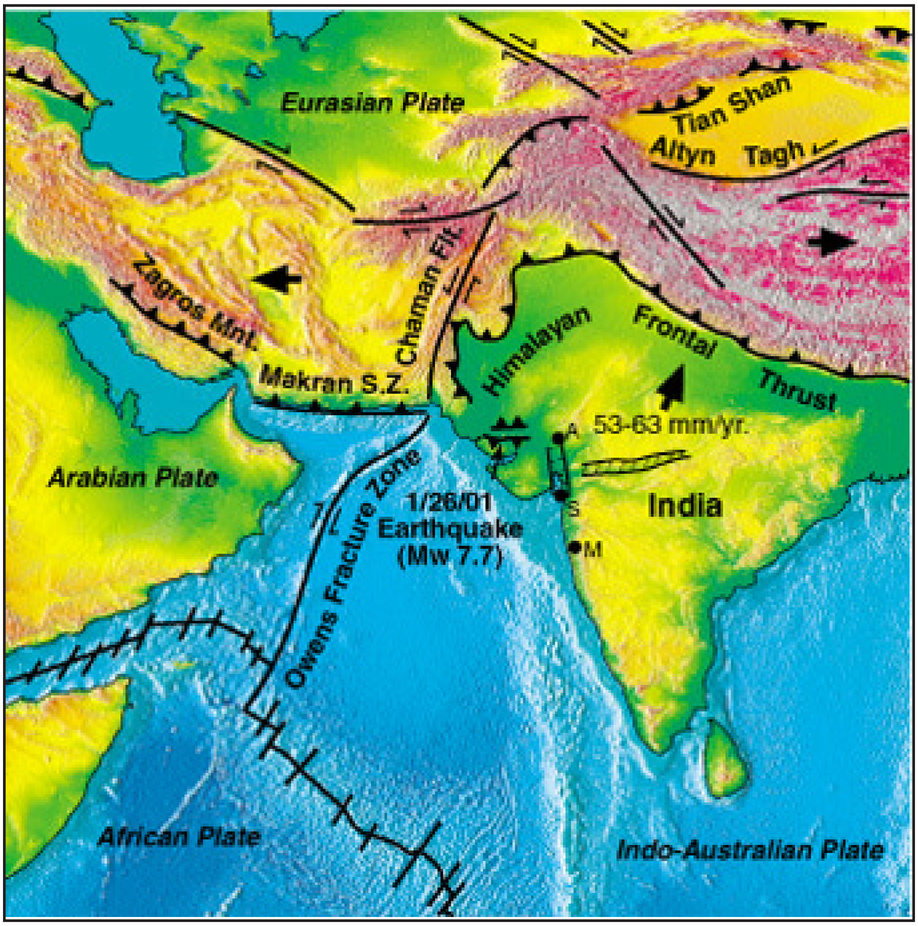

Figure 1 *Location and tectonic setting of the January 26, 2001 Mw 7.7 Republic Day Earthquake in northwestern India. Arrows show large scale movement of crustal blocks. A- Ahmedebas; S - Surat; M-Mumbai*

Introduction

A Mw 7.7 earthquake struck the Kachchh region of Gujarat State in western India at 8:46 a.m. (local time) on January 26, 2001 (Figure 1). This was the most damaging earthquake in the last fifty years in India. Over 20,000 persons are reported dead and over 167,000 injured; the number of reported deaths is expected to rise as additional information comes in. The estimated economic loss due to this quake is placed at around US$5 billion. The earthquake was felt in most parts of the country, strongly by people in multi-story buildings in Bombay (~570 km), and as far away as Calcutta, 1900 km to the east. The entire Kachchh region of Gujarat was extensively damaged, and several towns and large villages, like Bhuj, Anjaar, Vondh and Bhachau, sustained widespread destruction. Numerous recently built multi-story reinforced concrete frame buildings collapsed in

Gandhidham and Bhuj in the Kachchh region, and in the more distant towns of Morbi (~125 km east of Bhuj), Rajkot (~150 km southeast of Bhuj) and Ahmedabad (~225 km east of Bhuj). At least one multi-story building at Surat (~340 km southeast of Bhuj) collapsed, with accompanying casualties.

Tectonic Setting

The tectonic setting of the Kachchh is not well understood. It has been characterized as a stable continental region (SCR), but its proximity to the Himalayan front and other active geologic structures suggests that it may be transitional between a SCR and the plate boundary. The resolution of this issue would be important for full understanding of the geologic, seismologic and ground-motion implications of the earthquake.

As shown on the regional map in Figure 1, the Indian subcontinent is moving northward at a rate of approximately 53 to 63 mm/yr, colliding with the Asian plate, which is also moving northward, but at about half the rate of the Indian plate. The difference between the relative plate velocities produces an intercontinental collision forming the Himalayan Mountains and driving the eastward and westward movement of large crustal blocks away from the Himalayan orogen. The rate of contraction across the Himalayan Frontal Fault System (HFFS), and along the western boundary of the plate near the India/ Pakistan border is approximately 20 to 25 mm/yr. The rate of contraction across peninsular India south of the plate margin is about 3 ± 2 mm/yr.

The January 26th earthquake occurred less than 400 km from the junction of the Owens fracture zone, Makran subduction zone, the westernmost HFFS, and the Chaman fault, which form the plate boundary.

In addition, the Kachchh region is bounded by the Quaternary active Khambat graben to the east.

Within the Kachchh region, major structural features include east-trending folds and faults that deform Mesozoic, Tertiary, and possibly Quaternary units. The principal faults are the east-trending Katrol Hills, Kachchh Mainland, Island Belt and Allah Bund faults, the latter being the source of the ~M 7.8 1819 Kachchh earthquake. The January 26th earthquake appears to have occurred at depth beneath the eastern Kachchh Mainland fault. A series of anticlines occurs along the Mainland fault for over 220 km. This fold belt may have uplifted Quaternary fluvial terraces on its north flank and formed anticlinal structures and domes in Quaternary (?) sediments that underlie the salt flats in the eastern Little Rann near 23°17'N, 71°14'E. The presence of folds along the Kachchh Mainland and Katrol Hill faults involving possible Quaternary deposits suggests that there may be an active fold and thrust belt in the southern Kachchh region. However, the lack of prominent tectonic geomorphology suggests that the rate of crustal shortening is very low, on the order of a few mm/yr or less. In addition, the depth of the earthquake rupture, >17 km, suggests that the causative

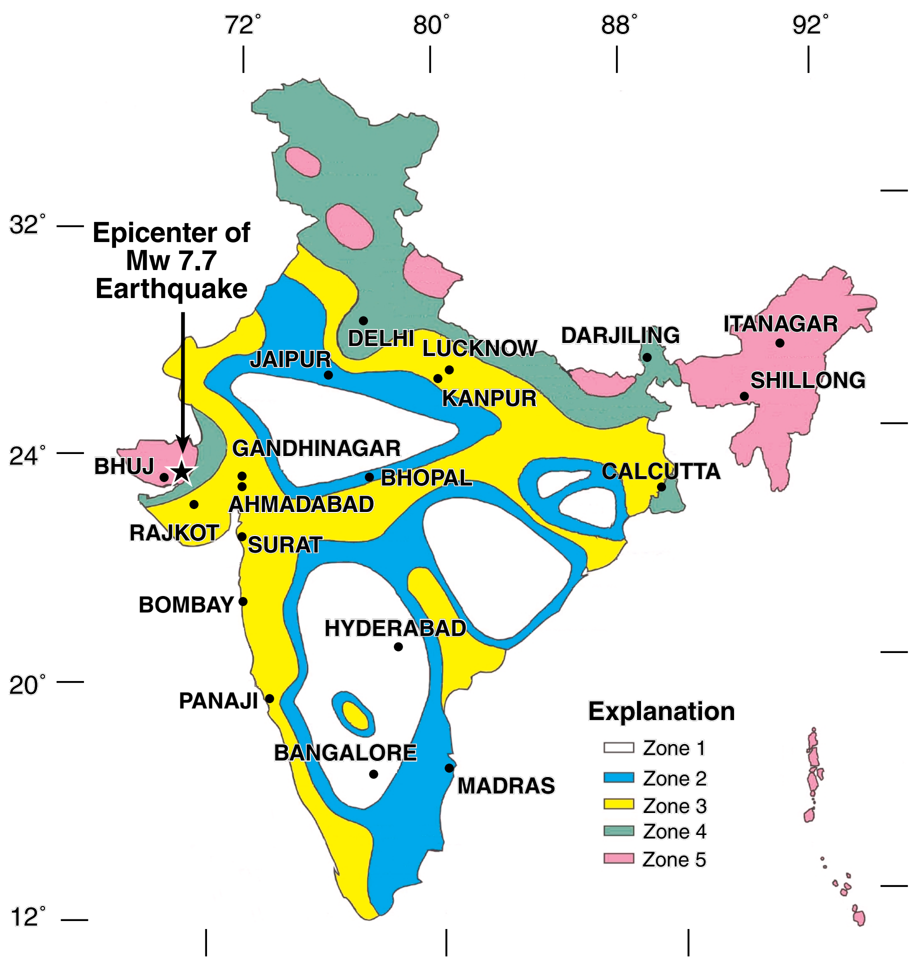

Figure 2 *Seismic zonation map of India. The epicentral region of the January 26, 2001 Gujarat earthquake is in Zone V. Note that both Ahmedabad (238 km east of epicenter), and Surat (357 km southeast of epicenter) where damage was extensive, are located in Zone III. (Map prepared by the Geological Survey of India)*

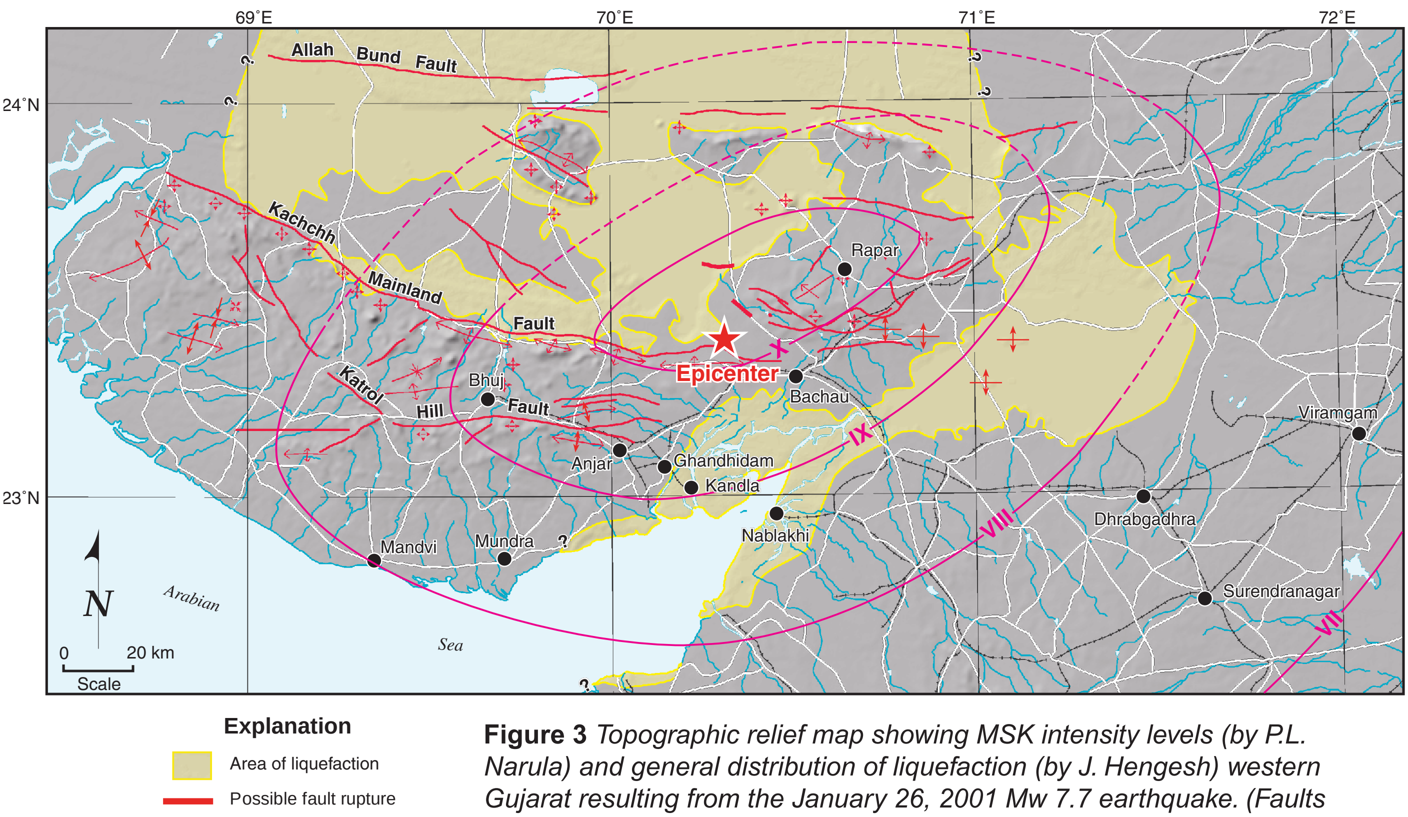

Figure 3 *Topographic relief map showing MSK intensity levels (by P.L. Narula) and general distribution of liquefaction (by J. Hengesh) western Gujarat resulting from the January 26, 2001 Mw 7.7 earthquake. (Faults from Malik, et. al., 2000)*

fault may lie beneath and be unrelated to the overlying fold and thrust belt.

The location of the earthquake within 400 km of the active plate margin, near the prominent bend in the plate boundary (~24.5°N), and in a region surrounded by Quaternary active structures and large magnitude historical earthquakes indicates that western Gujarat may be a transitional zone between the stable continental interior and the plate margin. Analysis of historical seismicity in the region shows a recurrence of approximately 200 years for large magnitude events such as the 1819 Kachchh and 2001 Bhuj earthquakes. Further, the presence of folds and faults involving Tertiary and younger sediments stands in contrast to the marked stability of peninsular India east of the Khambat graben, and indicates long-term tectonic activity.

The relatively high rates of historical seismicity in the Kachchh region, compared to peninsular India, is reflected in the higher seismic hazard assigned to the area on the seismic zonation map of India (Figure 2).

Earthquake Parameters

The epicentral coordinates of the mainshock obtained from teleseismic data are reported by the USGS to have been 23.36°N and 70.34°E. The hypocentral depth was between 17 and 22 kms, on a fault plane that strikes about N60^{0}E and dips 60^0 to 70^0 south with a slip direction of 62^0. The seismic moment of the event is estimated at 6.2x10^{28} dyne-cm. Initial modeling of slip distributions suggests a maximum displacement of 8 to 9 m at depth, and uplift of about 2 m, 15 km west of the epicenter.

The event had reverse motion, with a slight right-lateral component of slip. Strong ground shaking lasted about 85 seconds and lower level shaking lasted several minutes. Many survivors of the earthquake reported feeling two distinct pulses of shaking. These may relate to the separate arrivals of the P- and S-waves.

The closest strong-motion recordings are from Ahmedabad, where peak ground acceleration was 0.11g. This is anomalously high given the 225 km distance from the epicenter. Ahmedabad is located in the Khambat graben, which contains several kilometers of Tertiary and Quaternary sediments, and therefore the level of shaking may be related to basin amplification. Figure 3 presents a preliminary MSK intensity map for the earthquake. A maximum intensity of MSK X occurred over an east-northeast-elongated zone of approximately 2100 sq km. Most of Gujarat State lies within intensity VII or higher, reflecting the widespread damage and low attenuation of strong ground motion.

Geological and Geotechnical Effects

Fault Rupture: Although this was a large magnitude earthquake, no evidence of primary surface fault rupture has been identified. Aerial and field reconnaissance between the Island Belt fault to the north and the Gulf of Kachchh to the south, including the epicentral area, show that no primary surface rupture or sharp folding resulted from the earthquake.

Figure 4 *Extension failures at top of lateral spread in epicentral area. Figure on right shows sand boils in extensional cracks. (Photos by James Hengesh)*

A zone of ground deformation occurred within alluvial/sabka deposits near the northern margin of an anticline along the Mainland fault. The ground deformations include extensional ground cracking (Figure 4) and compressional bulging in a zone over 16 km long and 0.5 km wide near the epicenter. The features trend east-northeast, and are associated with extensive sand boils (Figure 4). The authors interpret these ground failures to be related to liquefaction and lateral spreading and not primary fault rupture.

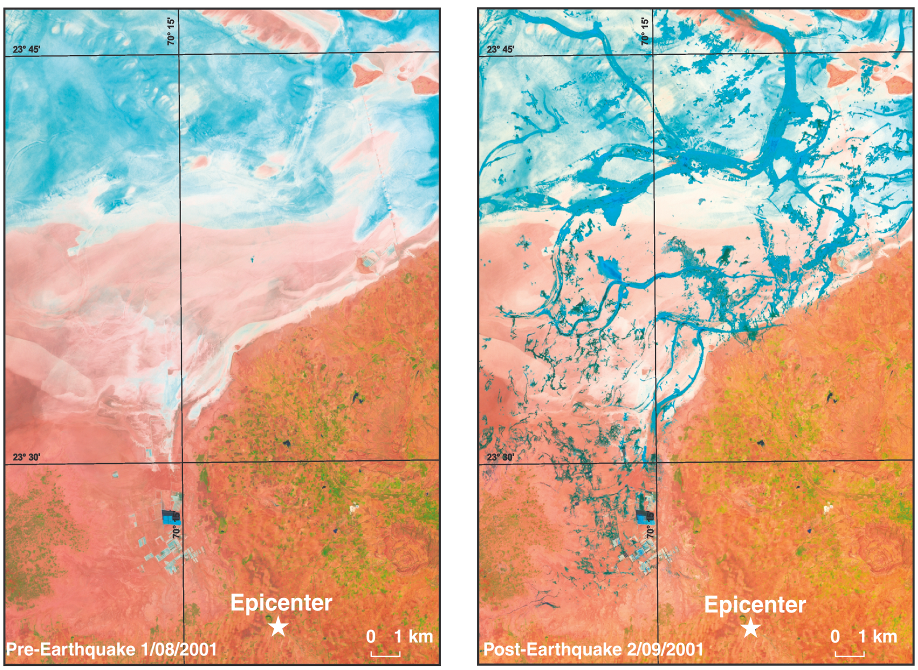

Figure 5 *Landsat TM image of January 26, 2001 Mw 7.7 earthquake showing distribution of liquefaction. Image on left taken before earthquake. Image on the right shows accumulation of surface water produced during widespread liquefaction. Subsidence of the ground surface may also have occurred due to compaction and consolidation and tectonic down-warping. (Raw scene courtesy of Ken Hudnut and Zhong Lu, USGS. Image processing by Andrew Barron, William Lettis & Associates.)*

In addition, secondary tectonic fault rupture is a possibility in two areas. Near the town of Manfara north of Bhachau, a northwest-striking rupture about 8 km long was observed with up to 32 centimeters of right lateral displacement. This feature may be a secondary tear fault in the hanging wall of the main thrust fault. At a second location southeast of Chung Dam, a northeast-striking rupture extends for several kilometers into an area of thin alluvium and locally may thrust bedrock over alluvium by up to 30 centimeters.

Liquefaction: The earthquake produced widespread liquefaction in the Great Rann, Little Rann, Banni Plains, Kandla River and Gulf of Kachchh (Figure 3). These areas contain low-lying salt flats, estuaries, intertidal zones, and young alluvial deposits, which typically have a high susceptibility to liquefaction. The extent of liquefaction shown in Figure 3 was inferred from local field and aerial observation and extrapolation to areas of similar susceptibility. Liquefaction was manifest at the surface as sand boils (Figure 4), lat-

Figure 6 Failure on upstream face of Fatehghadh Dam

eral spreads, and collapse features. Figure 5 shows satellite imagery of the epicentral area before and after the earthquake. The large amounts of water on the Banni plains after the event are a product of the liquefaction and possible consolidation of the ground surface. The authors estimate that approximately 10,000 km^2 of highly susceptible deposits liquefied during this earthquake.

Extensive liquefaction and lateral spread features occurred in the epicentral area (Figure 3). Some of these features have been reported by others as primary fault ruptures; however, their association with sand boils, arcuate shape, change in sense of deformation along the head, toe and lateral margins, and lack of noticeable vertical land-level changes favor a non-tectonic interpretation. The authors speculate that tectonic warping provided the driving force for the lateral movement of the liquefied soil on the previously very flat slope.

Liquefaction caused damage to several bridges, the Ports of Kandla and Navlakhi, and numerous embankment dams in the epicentral area. Seven medium-size earth dams (Shivlakha, Rudramata, Fategad, Suvi, Kaswati, Tapar, and Chang) and 14 smaller earth dams were damaged during the earthquake, providing a wealth of new information on the response of zoned embankment dams to strong ground shaking. Liquefaction of the foundation soils beneath these dams produced moderate to severe failure of the upstream, and, locally, the downstream faces of the dams (Figure 6).

Slope Failure: The earthquake produced numerous rockfalls from steep slopes and road cuts. Rock falls included topple failures and surficial ravelling. Similar to liquefaction, these rock failures were observed over an area of about 10,000 km^2. These slope failures were most prominent in the areas near Bhuj and Bhachau. No large-scale rotational failures were observed on native slopes.

Buildings

The earthquake destroyed about 300,000 houses and damaged another 700,000. Buildings in the affected area can be placed into two broad groups: 1) non-engineered dwellings made with load-bearing masonry walls supporting a tiled roof or reinforced concrete (RC) slab roof; and 2) RC frame buildings with unreinforced masonry infills. Indian seismic codes are relatively well developed for buildings, and code provisions are available for different types of construction including low-strength masonry buildings. However, most buildings in the region did not comply with the seismic code provisions since the codes are not mandatory. For multi-story RC buildings, Indian codes contain lateral force provisions as well as ductile detailing requirements in line with current international practices, but again, very few multi-story buildings fulfill seismic provisions. Most government organizations attempt to comply with the code requirements; however, in the private sector where property developers invest in the building for sale of residential units to individuals, there is pressure to minimize structural costs. Moreover, many architects insist on slender columns so as to make them flush with the infill walls; a building may have column width as low as 125 mm, or 5 inches.

Masonry Construction: Non-engineered construction constitutes over 95% of the building stock in the Kachchh region. The different types of masonry used in the region include 1) random rubble stones with mud or cement mortar, 2) small or large cut stones in mud/cement mortar, 3) burnt-clay bricks in mud or cement mortar, and 4) solid or hollow cement blocks in cement mortar. In the meizoseismal area, masonry buildings collapsed, killing a large number of people. The performance of stone masonry with mud mortar has been, of course, particularly poor. On the other hand, masonry buildings up to about four stories did well in Ahmedabad (about 225 km from the epicenter), whereas a number of RC frame buildings in Ahmedabad collapsed or were severely damaged.

The heavy damage to masonry construction results from the poor performance of mortar and the use of heavy and loosely formed roofs. Similar observations were made after other earthquakes in India in recent years. The 1993 Killari earthquake caused extensive collapse of random rubble masonry walls owing to lack of integrity within the walls, and the 1999 Chamoli earthquake showed the lack of integrity in the heavy pitched roofs composed of tiles supported on wooden rafters and purlins. Notable deficiencies observed in the dwellings in the area affected in this earthquake include walls not adequately connected to each other and to the roof, separation of the 0.4-0.6 m-thick masonry walls into two distinct wythes, and failure of the rather heavy "Mangalore" clay tile roofing system with thick wooden logs as purlins and rafters.

Among the non-engineered construction in the Kachchh area, use of very large stone blocks (0.25 m by 0.40 m by 0.60 m) in masonry walls, with mud mortar or low strength cement mortar. These exhibited very poor performance. Understandably, the loosening of these blocks owing to lack of plumb in construction and to the action of the out-of-plane earthquake forces often led to the collapse of the wall, leading to the overall instability of such dwellings.

Figure 7 *The building adjacent to this open first story building at Ahmedabad collapsed (Photo by Sudhir K. Jain)*

The quake-affected areas of Kachchh and Saurashtra (Saurashtra means *one hundred nations*) have numerous historical buildings, tombs, minarets and pagodas in stone masonry. Many of these structures collapsed or sustained heavy damage during the quake. For instance, in the districts of Kachchh and Rajkot, of the 250 heritage structures inspected by the Indian National Trust for Art and Cultural Heritage (INTACH), about 40% were reported as either collapsed or severely damaged, while only 10% were reported as undamaged. An immediate challenge is to restore these heritage structures to the maximum extent possible.

Reinforced Concrete Frame Buildings: RC frame residential buildings are generally 4 or 5 stories or "high rise" (up to ten stories). The buildings are of two types: those with a first story having very few or no infill walls (open first story) in order to accommodate vehicular parking; and those without an open first story. Numerous buildings with open first stories collapsed (Figure 7).

Buildings with an open first story create the classical "soft story" situation known for vulnerability during earthquakes. Most of these buildings were designed only for gravity loads and not for lateral forces, resulting in small column sizes. For instance, the column sizes for the 4-5 story buildings are usually about 230 mm x 450 mm, with ties consisting of mild steel 6 mm diameter bars at a spacing of about 200 mm. The column sizes for taller buildings are only a little larger, usually 230 mm x 600 mm, with 8 mm diameter ties at a spacing of 200 mm. Ductile detailing is absent in most buildings, making the columns brittle. Finally, the quality control during construction is often inadequate. All these factors contribute to poor performance of the soft first story.

The earthquake also provided examples of collapses of upper or intermediate stories in RC buildings (Figure 8). In keeping with gravity load design concepts, the column reinforcement is often lapped just above the beam-column joint. Inadequate lap of column reinforcement at the joint, or abrupt reduction in column dimensions may have resulted in these collapses.

The RC frame buildings built by government engineering departments suffered less damage than the privately constructed ones. Most such government buildings suffered only nonstructural damage.

Buildings without an open first story, i.e., those with infilled first story walls, generally performed much better even though they also sus-

Figure 8 *Intermediate story collapse of 6-story RC building at Bhuj. (Photo by C.V.R. Murty)*

tained damage in the infill separation from the frame and diagonal cracking in the infills. Again, most of these buildings were not designed for lateral forces. Infill walls, even those of unreinforced masonry, contribute significantly to the lateral strength and stiffness of the building. In normal residential buildings, the story height and the panel length are not unusual and brick infills have generally not shown vulnerability to out-of-plane collapses.

The performance of RC frame buildings in this earthquake is significant for India and many other developing countries, where seismic design is not conducted for most buildings and where unreinforced masonry infills are extensively used as nonstructural components. Building performance in this earthquake suggests that the brick infill walls, with the typical bay dimensions and story heights for residential buildings, are relatively stable against out-of-plane collapse and can therefore be relied upon to provide in-plane lateral strength and stiffness to the building. The design of new buildings and the seismic retrofit of existing ones should consider the beneficial effects of the masonry infill walls' strength and stiffness. Code provisions need to be developed for this purpose.

Another interesting feature of the earthquake was damage to numerous water tanks on top of multi-story buildings built integrally with the RC frame (Figure 9). The capacity of these tanks is relatively small and these acted as cantilever appendages above the building.

Many RC moment-resisting frame buildings with open first stories had severe damage to the first floor columns, but did not collapse owing to the presence of RC elevator shafts. RC elevator shafts themselves had significant diagonal shear cracks, indicating that the soft-story system imposed large demands on the

Figure 9 *Water tanks atop multistory buildings sustained severe damage. This five-story building was located in Bhuj. (Photo by Jaswant N. Arlekar)*

shear core in the open story. In some instances, there was insufficient lateral load transfer between the RC elevator shafts and the rest of the structure, at least two such structures collapsed with the RC elevator shafts intact.

A special feature of RC frame buildings in Ahmedabad deserves mention. The city by-laws limit the total covered area on a property, but balconies are not counted in the covered area. Furthermore, balconies can be covered. Therefore, designers adopt a structural system that has first floor beams cantilevering out from the end bays by about 1.5 m and columns along the perimeter of the building floating at the tips of these cantilevers. In most cases, these cantilever beams showed diagonal shear cracks.

Detailed study is needed on the effect of local site amplification in the performance of the buildings in the city of Ahmedabad. The city is built on thick alluvium deposited by the Sabarmati River that runs through the town. Ground-motion records obtained by the Department of Earthquake Engineering of the University of Roorkee from the basement of the Passport Office Building there showed no predominant long period characteristics like those recorded in the Mexico City during the 1985 earthquake. However, the elastic acceleration response spectrum of the ground motion indicates a relatively extended acceleration-sensitive region of the spectrum for periods up to 0.80 sec.

Precast Construction: Some single-story school buildings in the Kachchh region are made of large panel precast RC components for the slab and walls, and precast RC columns. A typical design using this construction has been recently replicated all over Gujarat, including in the affected region. Approximately one-third of 318 such schools in the Kachchh region had roof collapses (Figure 10). Inadequate connection between the roof panels led to lack of floor-diaphragm action, and insufficient seating and anchorage of the roof panels over the walls and beams led to dislodgement of the precast roof panels from atop the

Figure 10 *A school at Gandhidham with precast components has collapsed roof panels. Traditional buildings at the same school did not collapse. (Photo by Sudhir K. Jain)*

walls. This has been observed in many past earthquakes across the world. Most of the failures of precast building systems resulted from these problems. Precast technologies are not popular in India and their suitability in high seismic areas has not yet been experimentally established. There is a serious need to determine the suitability of such construction before any more precast buildings are erected in seismic areas.

Improper Post-earthquake Strengthening of RC Buildings: With collapse of numerous RC buildings in Ahmedabad and severe damage to the columns of others, efforts to repair and strengthen buildings were begun by local builders and contractors immediately after the earthquake. In many cases, the damaged first floor columns were jacketed with new concrete, usually in an improper way. For instance, new steel frames that were installed around existing columns to encase the concrete rested on the finished ground floor and were not carried to the foundation (Figure 11). Similarly, the new frame was not adequately connected to the beams above. In some cases, the plaster of beams and columns was not removed. In others, a structural steel member was placed adjoining the damaged RC column, and both column and the adjoining steel member were jacketed together with concrete. In this instance, the steel column was taken below the floor level but still not extended to the foundation. An urgent need was strongly felt in the affected area for structural engineers with expertise in earthquake-resistant construction, but there were not many such engineers available.

Bridges

The affected area has several major highway and railway bridges. However, the majority of the bridge damage is confined to those in the district of Kachchh. Bridge damage included: 1) pounding of adjacent simply-supported spans at the deck level in the longitudinal direction; 2) transverse movement of the superstructure decks; 3) damage to bearings, bed blocks and lateral restrainers; 4) distress of the masonry arches and RC and masonry piers; 5) damage to abutment wing walls; 6) slumped approach embankments; and 7) collapse of handrails. Consistently, the connections between the superstructure and the substructure proved to be the weakest link. Some RC slab culverts on stone masonry abutments sustained damage at the seating of the span. A few RC pipe culverts also collapsed in the area that had shaking of intensity X. In general, there were no dramatic bridge collapses as the region did not have bridges with tall piers or flexible superstructures.

The only road link between the Kachchh and Saurashtra areas is the 30-year-old 1200 m-long 2-lane highway bridge at Surajbadi. It is a multi-span balanced cantilever RC box-girder bridge with suspended spans. The substructure consists of 4.5 m-tall RC piers on RC well foundations (caissons), which rest on competent soil underneath the overlying blue marine clay. This bridge sustained significant damage during the earthquake. All bearings under the superstructure spans over the piers were damaged. The rocker and roller bearings at all the piers were removed, and the bridge is temporarily resting on wood blocks. The foundation under pier 12, numbered from the north end was significantly tilted thereby shifting the alignment of the highway, causing the superstructure to move laterally. Traffic was stopped for two days before the bridge was temporarily restored for slow, single-lane traffic. The bridge also suffered damage due to pounding of the superstructure spans at the balanced cantilever joint locations. Extensive liquefaction was observed at the ground surface adjacent to the bridge foundation.

About 60 m east and parallel to

Figure 11 *Improper concrete jacketing of the columns was widely practiced in Ahmedabad immediately after the earthquake. Note that the new reinforcement simply rested on the floor, and was not anchored to the slab/beam at top (Photo by Sudhir K. Jain)*

the above bridge, a new 39-span two-lane highway bridge was under construction. Each span of this new bridge is 32.2 m long and made of three precast, pre-tensioned, prestressed simply-supported girders with a deck slab and with a small cantilever overhang at each of the two ends. The substructure consists of a T-shaped RC pier, supported on a well foundation or caisson. Each well foundation supports two piers, one each on two adjacent spans. The bridge was provided with RC up-stands at the ends of the pier caps to act as restrainers to limit transverse displacement of the superstructure. Neither the piers nor the well foundations sustained any damage during the earthquake, but the pounding of the superstructure girders damaged almost all of the RC up stands (Figure 12). Indeed, these lateral restrainers were called on during the earthquake. Damage to the deck joints due to pounding of two adjacent spans was also observed.

About 1 km further east and parallel to the two bridges mentioned above is a 30-year-old single-line broad-gauge railway bridge. The superstructure consists of 62 spans of 18 m-long simply supported, steel plate girders. The rails are fastened to the wooden sleepers that are directly anchored to the steel plate girders. The substructure consists of 4.5 m-tall RC piers supported on well foundations. The bridge substructure was designed for a horizontal acceleration coefficient of 0.1 g. The earthquake caused dislocation of girders on several bearing plates, which affected the track alignment. Also, the approach embankment on the south side settled. Within three days, the girders were brought back to their original position, the approach embankment was repaired, and train traffic was restored.

The two-lane four-span RC highway bridge at Vondh (MSK intensity X) exemplifies poor seismic design of a bridge superstructure. The superstructure consisted of deep girders connected with a top slab in three of the spans and just a slab in the short end-span at the north end. Since the depth of the end-span slab at the north end is smaller than the girder depth of the adjacent span, the pier supports bed blocks of unequal height for the two spans. The area at the bridge site suffered extensive liquefaction. Pounding of the deeper girder with the taller bed block caused severe damage. Also, elastomeric bearings at the other two piers and the south-side abutment showed severe straining.

A two-lane ten-span prestressed concrete I-girder highway bridge supported on tall RC A-frame substructures across the Rudramata

Figure 12 *The new bridge across Little Rann of Katchchh at Surajbadi was provided with concrete upstands to act as seismic stoppers in the transverse direction. All the stoppers were damaged by pounding of the superstructure, indicating their successful use (Photo by C. V. R. Murty).*

river 12 km north of Bhuj towards Khawda sustained nominal damage in the form of tilting of steel bearings at one of the intermediate supports, loss of cover of the concrete bed block at the abutment, and damage to the handrails. Damage to the road surface indicated severe pounding of the decks, particularly at the abutments.

The 420 m-long, two-lane ten-span RC girder-slab India Bridge, north of Khawda Island across a portion of the Great Rann of Kachchh, also sustained damage. The 1973-built bridge with simply-supported spans consisted of three longitudinal girders of 4 m depth. The adjoining soil exhibited widespread liquefaction. The bridge suffered damage to the steel bearings and recently filled grease in the bearing boxes was squeezed out. The concrete bed blocks supporting these bearings were also damaged. The stone masonry wall piers with RC plastering showed severe spalling at the lower levels. The wing walls at the abutments moved by about 150 mm. The approach embankments on the south side showed cracks at the crest. The damage to the road surface at piers 1, 3, 5, 7 and 9 suggested significant pounding of the superstructure decks in the longitudinal direction. Some of the handrails of the deck collapsed.

Port and Other Industrial Facilities

Coastal Gujarat is home to numerous industrial establishments that transact significant business through seaports at Kandla, Mundra and Navlakhi. No significant damage was reported at the Mundra port. However, the facilities at the Navlakhi and Kandla ports, built on highly liquefiable artificial fill over old creeks, were significantly affected by the earthquake, owing to both structural inadequacies and liquefaction. Navlakhi port, located on the Gulf of Kachchh, was severely damaged. At the port, one old sea wall and a newly constructed jetty completely failed, collapsed and partly washed away. Also, a stretch of over 2.5 km of the rail line and road connecting to the port failed due to landslide-induced slope failure.

Kandla Port Cargo-Handling Jetties and Adjoining Structures: The wharf structures at the Kandla port include RC jetties covering over 2 km of the waterfront for berthing ships and handling dry cargo. The older jetties are supported on 0.5-m-diameter RC piles at 4.5 to 5.5 m spacing in two directions in plane, and the relatively newer are supported on 1.0 m-diameter RC piles at similar spacing. The lengths of the RC piles are about 40 m on the waterfront and 20 m on the inside, with at least 15 m of embedment from the mud-line. The quake caused widespread liquefaction at the site; the landfill settled approximately 15 cm. Lateral spreading of the liquefied soil at the jetties led to lateral translation of all the 0.50 m-diameter piles under the old jetties, resulting in flexural cracking. Shear cracking was also observed in some piles along the innermost row of piles parallel to the wharf, where the mud-line was shallower. However, the newer jetties supported on 1.0 m-diameter piles performed well. The giant tower cranes for handling cargo at these jetties performed well; there were no container cranes at this port.

Some of the other notable damage at the Kandla port is included in the following:

1. The knee-bent RC frames at one jetty sustained flexural and shear cracks at the outrigger beam-column joint;

2. A 50-year-old RC warehouse building sustained severe damage (cyclic shear cracks) to the exterior short columns at the ventilators, namely, opening of ties and buckling of longitudinal steel. The roof of the building

settled above these perimeter columns. The interior columns showed little or no damage;

3. Liquefaction resulted in severe undulations of floor tiles of the container terminal;

4. Another storage shed with a precast RC truss roof system sustained partial collapse of the roof owing to failure of the welded connections between the trusses and the interconnecting ties; the brittle welds at the face of the ties and the bottom chord of the trusses had been pulled apart. The 90 m-long shed has an expansion joint of 25 mm at 42 meters from one end; the quake caused a further separation of 125 mm at this expansion joint.

5. The 22 m high six-story RC frame Port Signal and Control Tower building tilted 15° toward the water due to liquefaction of the underlying soil and consequent lateral spreading towards the bay. The building was supported on a pile foundation.

6. The soft-first-story office building adjoining the control tower building collapsed, due to both soil and structural defects.

Kandla also has six jetties for liquid cargo of oil and chemicals; the first and fourth jetties were severely damaged, and the second jetty was partially damaged. The damage is similar to that sustained at the dry cargo jetties. Support anchors at the end of the walkway between Jetties 2 and 3 completely sheared off due to liquefaction-induced ground deformation. Three RC surveillance towers in the vicinity nearly or completely collapsed.

Fertilizer, Chemical and Liquid Storage Facilities:

The Indian Farmers Fertilizer Corporation Limited (IFFCO) plant at Kandla is about 20 years old and sustained serious structural damage. Widespread liquefaction occurred at the site. Serious damage at the plant included collapse of the Conveyor Belt Facility (Figure 13) due to the failure of the underlying concrete truss system, out-of-plane collapse of concrete block infills from within the RC MRF at the Manufacturing Unit Building, collapse of prestressed concrete roof trusses at the Potash Storage Facility, collapse of steel truss roofing at the Bag Loading Unit, and large settlement of the Ammonia Storage tanks.

Figure 13 *Collapsed product conveyor from manufacturing unit to storage at the IFFCO plant at Kandla (Photo by Praveen K. Malhotra)*

There are numerous large ground-supported liquid storage tanks at Kandla, with a cumulative storage capacity of 1.7 billion liters. The tanks generally were constructed on sand pads over stone columns to mitigate the potential for liquefaction. At the JR Enterprises Tank Farm, the 14 m-diameter, 18 m-high welded steel tank (16 mm thick at base and 8 mm at top, with a 12 mm-thick base plate) containing Acrylonitrate to over 90% height sustained tensile failure at the shell-base junction along a 2 m segment of the circumference due to uplifting forces. The tank is unanchored at the base and is supported on 0.6-m diameter 27-m long piles. The tank also suffered rupture of sprinkler water piping. The concrete pedestals supporting the piping at this site indicated settlements up to 5 cm. Another 780kL-capacity, 10 m-diameter, 10 m-high welded steel tank filled to 75% with paraffin (HEP) sustained 5 to 8 cm of liquefaction-induced settlement. In no case, however, was the compression-based “elephant foot” buckling observed.

A 40-year-old fire-fighting, water-storage, welded-steel, ground-supported tank of 1300kL capacity rests on a sand pad, and has a shell thickness of 12 mm at the base and 6 mm at the top. This tank at the Indian Oil Corporation campus has no stone columns underneath the sand pad and sustained uneven settlement up to 5 cm. Ground shaking also caused uplifting of the base and

Figure 14 *Collapse of the electric sub-station at Anjar was a major setback for electricity suppy to the region (Photo by C. V. R. Murty).*

consequent fracture of the attached piping.

Pipelines: The Reliance Petrochemicals Refinery at Jamnagar sends refined oil to the Indian Oil Corporation facilities at Bhatinda and Hazira through a 1500 km-long 0.40-0.55 m diameter steel pipeline. The pipeline has six draw-points enroute. The prestigious facility sustained no damage.

Other Structures: The area has numerous salt factories. The factory buildings accommodating different processing units are highly irregular in geometry and structural systems. Many factory buildings sustained partial collapse and severe damage. In the Little Rann of Kachchh, many salt ponds experienced failure due to seiche and failure of the perimeter levee system.

The epicentral area also has a large number of engineered structures like oil refinery plants, tall RC stacks and chimney stacks up to 90 m height, TV towers (300 m at Bhuj, and 170 m at Ahmedabad), steel high-tension electrical transmission towers (up to 80 m high), steel communication towers (up to 30 m high), RC cooling towers (up to 60 m high), steel frame structures, and RC elevated water tanks on frame and shaft staging. These structures had no damage or only minor damage, with the exception of a few RC elevated water tanks that collapsed.

Lifelines

Transportation: Immediately following the earthquake, there was no road and rail access to the Kachchh region from the rest of the state. The old highway bridge at Surajbadi across the Little Rann of Kachchh was damaged and was closed to traffic for two days. Thereafter, restricted single-lane traffic was allowed until March 2nd, when all traffic was diverted to the new bridge that was under construction at the time of the earthquake.

The rail network was made operational into Gandhidham on January 29th. The Gandhidham to Bhuj railway segment was closed at the time of the earthquake for gauge conversion and was scheduled to become operational on January 31; this segment became operational on February 3rd.

Communications: Fiber optic cables providing communications to the region snapped. Telephone communications with Bhuj were restored in two days, but remained a weak link.

Electrical Power: Power supply in the area comes primarily from coal-fired thermal power plants at Panandhro (~180 km NW of epicenter), which experienced only minor damage. This electrical supply is supplemented by a coal-burning plant in Ahmedabad and a nuclear plant 400 km southeast of the epicenter; neither was damaged. Over a dozen substation control buildings (unreinforced masonry) collapsed, and about 45 were damaged. The control building damage had the greatest impact on the overall system failure. There was no damage to transmission towers. The first major substation (132 kV) was brought back online in three days in Bhuj, and the first 220 kV substation brought back on line in five days in Anjar. As of February 5th, an estimated 80% of the region's power had been restored.

One of the major bottlenecks in power transmission was the collapse of the 220 kV substation building at Anjar (Figure 14). The communications system and power protection system failed due to collapse of the battery rack. Workers could not immediately enter the control building to repair the battery rack because of collapse or the threat of collapse of the roof. The unanchored control panels inside did not topple. In the yard, all transformers derailed, but no bushings broke. The fluid seals of three-line breaker poles failed, and one of the circuit breakers fractured. This failure led to the complete blackout of Anjar and five villages around it, Gandhidham city, and the IFFCO Campus at Kandla port.

Water Supply: The Kachchh region has over 800 villages and towns. More than 90 percent of them are supplied by the 140 Regional Water Supply Systems constructed and operated by the Gujarat Water Board (GWB). The region is served primarily by groundwater pumped from a limestone formation in the south central Kachchh region. The farthest supply point from this source is 250-300km. The region has been going through a drought. Prior to the earthquake, about 150 villages were being at least partially supplied by water imported in tank trucks; this number may go up to 200-250 by the upcoming summer.

Some of the well casings (0.25 m diameter 6mm thick steel) were bent, and some power cables serving the submersible pumps snapped. At Bhuj, 6 of 16 well casings collapsed. Some wells with slotted casings were filled in with flowing sand. The water was turbid in some wells for about two hours after the earthquake. There was no emergency power at the wells and, hence, some of them could be made functional only after electrical power was restored to the area.

Water quality was tested before recommissioning the wells. After the earthquake, 16 of the 300 wells tested showed sulfur and metal contaminants. In general, water in the region has always had a high dissolved solids content of 600-1200 ppm, in contrast to 20 ppm for a mountain watershed.

Gandhidham is served, in part, by surface water and from Tapar dam. Water is treated at a conventional treatment plant and transmitted 30 km into the city. During the earthquake, liquefaction in the bottom of the reservoir stirred up anaerobic sludge, which caused major concern for water quality. The top 5 m of the intake structure at Tapar collapsed and required emergency restoration before water could be pumped out of the reservoir. The first kilometer of pipe (cast iron with rubber joints) had to be replaced due to leakage. Tapar dam itself sustained liquefaction-induced slope failure damage and will require repairs prior to the summer monsoon season.

The clarifier at the water treatment plant was damaged and is being bypassed, applying raw water directly on the filters. This reduces the overall plant capacity. It is estimated that it will take 45 days to repair the plant. The clarifier failure is almost the same as that at the Rinconada Water Treatment Plant during the Loma Prieta earthquake, where a baffle failed due to sloshing.

An estimated 20 to 30% of the pipeline transmitting water from the water treatment plant to Gandhidham will require replacement. Currently 40% of the water is being lost due to leakage in the cast iron, reinforced concrete, and asbestos cement pipes used in various sections along the alignment. Leaks seem to be at stream crossings.

The GWB reported that there is extensive damage to pipelines, particularly those running north across the Rann of Kachchh, where there was extensive liquefaction.

Approximately 250 30-m-high elevated RC water storage tanks in the Kachchh region performed well. However, five elevated tanks in the Malya-Morbi region south of the Gulf of Kachchh failed. All the tanks are constructed following typical government design.

Sewage: Five cities in the Kachchh district, including Gandhidham, Adepur, and Bhuj, have partial or complete sewage collection and treatment systems. Bhuj has an oxidation pond for sewage treatment. There were no pipe collapses, but the system has not been fully tested.

Rescue, Relief and Rehabilitation

The Kachchh region of Gujarat is known for high seismic hazard (see Figure 2), yet there was no disaster management plan in place to handle the earthquake emergency, and the government of Gujarat (GoG) was unprepared for a disaster of this scale. In India, disaster management is the responsibility of state governments, with the federal government (GoI) assisting with logistical and financial support. After the earthquake, GoG and the GoI coordinated well, at least partly because the same political party is in power at the state and federal level.

Rescue Efforts: Government response was hampered because the earthquake occurred on the Republic Day Holiday and much of the government machinery was involved in the ceremonial activity. The time of the quake (8:46 a.m.) coincided with flag-hoisting ceremonies in many places. In some locales, this actually saved numerous lives since many officials, school children, and families had gathered on open ground for the ceremonies; however, in Anjar, about 300 children marching in narrow streets for the Republic Day parade could not escape when buildings collapsed from both sides, trapping them.

An emergency control room in the state capital of Gandhinagar became operational by 9:30 a.m., with all the facilities of a well-equipped EOC. However, repeated breakdown in communications with the rest of the state and New Delhi seriously marred its effectiveness. The telecom building in Bhuj was severely damaged and several telecom officials were killed by falling debris. The fibre-optic cable that provided connectivity to the

Figure 15 *Upper story of the District Collector's office at Bhuj collapsed. The District Collector is the most important official for handling emergencies in the District (Photo by C. V. R. Murty).*

Kachchh region was broken, resulting in isolation of the district from the rest of Gujarat. Even the cellular phone coverage was interrupted. Communications with Kachchh were partially restored two days later, but remained the weakest link in response operations.

The control rooms in places other than Gandhinagar were makeshift in nature, lacking in both essential facilities and operational focus. While the information from Kachchh trickled in slowly, news of collapses of multi-story buildings and consequent deaths poured in from Ahmedabad. The GoG focused on the situation in the city, but rescue operations were hampered by the lack of expertise and equipment in dealing with the collapses of multi-story RC buildings; this being the first earthquake in India to have caused such collapses.

The collapse of the District Collector's office building in Bhuj (Figure 15) had a psychological impact on the district administration's capacity to deal with rescue efforts. In addition, almost all government employees in Kachchh suffered personal loss, and it was difficult to mobilize individuals for rescue operations. This was a serious problem at the state level too: the Relief Commissioner lost his sister-in-law, who lived in Bhuj.

The scale of disaster in Gujarat was so extensive that search and rescue operations were overwhelmed. The City of Ahmedabad ran short of cranes and earthmovers to rescue people from the collapsed buildings. In the Kachchh region, the towns of Bhuj, Bhachau, Anjar and Rapar, the city of Gandhidham, and more than two hundred villages sustained severe to complete devastation. There were also deaths and extensive damages in the neighbouring towns of Surendranagar, Patan, Jamnagar, Bhavnagar, Surat, Anand, Rajkot and Banskantha. It was impossible for the GoG to send rescue teams with cranes and earthmoving equipment to every site of devastation, but neighbouring states and private construction companies and industrial houses in the region contributed to the rescue efforts. In many cases, large bulldozers could not reach downtown areas due to narrow streets blocked by rubble.

As is the case in all such disasters, rescue in the initial hours was carried out by local survivors of the disaster. Later, the Indian Army performed most of the rescues and flew in heavy equipment. The Army also set up relief camps, distributed food, and provided medical assistance including surgical units. The Military Hospitals in the Kachchh region, Ahmedabad and Pune treated the injured. The army also provided much needed security for property. On the whole, the Indian Army received tremendous acclamation for their efforts.

Relief Operations: Relief assistance began arriving in 72 hours from both within and outside the country. Numerous non-government organizations (NGOs), industrial houses and religious organizations provided relief assistance in the form of cooked food, water, blankets, tents, and medicine. The governments of several other states in India contributed significant relief materials. The GoI welcomed all foreign agencies that wished to help in the rescue and relief. As a result, a large number of countries sent teams to participate in rescue and relief. The Indian Air Force (IAF) airbase at Bhuj was critical for receiving emergency supplies and personnel. Even though the IAF sustained significant losses at Bhuj and ten personnel were killed, the runway was made operational by the afternoon of the first day. Bhuj became one of the busiest airports in India: in the first five days following the earthquake, the otherwise sleepy Bhuj airport handled 800 landings and departures, which is more than the traffic at the Delhi and Mumbai airports combined.
After the first few days of apparently disorganized and weak response, the GoG improved coordination of the rescue and relief effort. A senior officer was appointed as the Relief Coordinator at Bhuj, and a new District Collector took charge. By this time, road, rail, and telecom links had been restored, thanks to the extraordinary dedication of officials of these departments. A coordination unit was set up at Bombay to facilitate the handling of international relief.

While there was a glut of relief material in the villages on the main road, adequate relief did not reach many of the villages in the interior areas. Some of the problems were 1) poor coordination with the NGOs, which distributed relief material as they felt appropriate, which did not necessarily mean optimal distribution of relief material for the entire affected population; 2) distribution of relief material through the public distribution system, which required people to produce the ration cards that they used during normal times; and 3) the relief materials were sometimes inappropriate for needs of the people (e.g., in one instance, tinned sardines were supplied to the people of Kachchh, who are predominantly vegetarian). As the days passed, temporary shelters for the homeless emerged as the most pressing need. The supply of tents was far short of the demand.

Rehabilitation Plans: The GoG is planning for the long-term rehabilitation of the people rendered homeless, and has announced liberal financial assistance for those whose houses were partially or fully damaged. The rehabilitation plans provide for relocation of villages sustaining more than 70% damage to new locations, when the local village government so recommends. The entire rehabilitation scheme envisages a very strong participation of the NGO sector. Reconstruction of the region is a daunting task by any standard but, despite the devastation, both the government and people of Gujarat show remarkable confidence that Kachchh will rise again, and very soon. Kachchhis are known for their strength, courage and resilience (Figure 16).

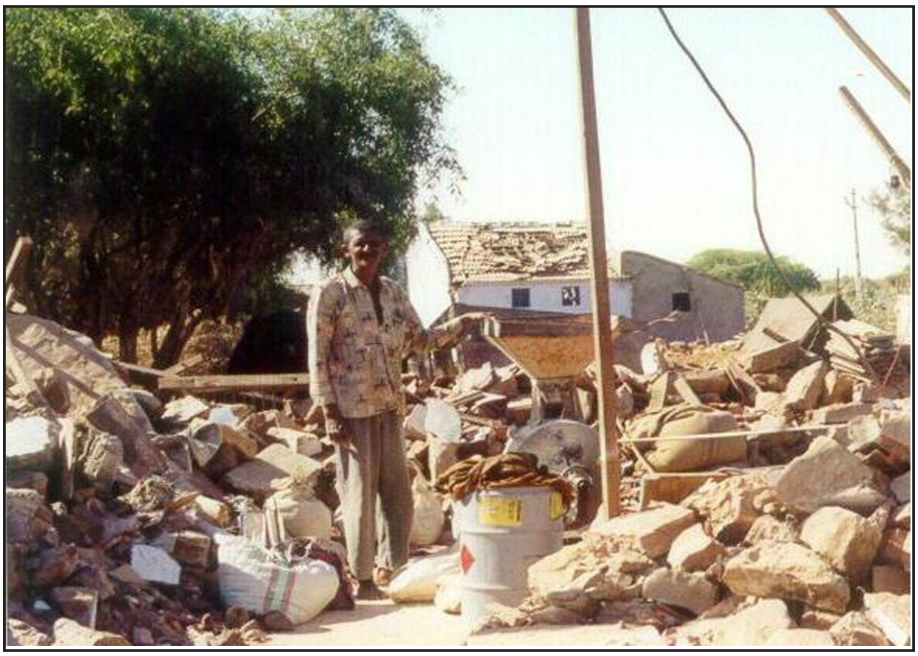

Figure 16 *This man is operating his small wheat grinding machine amidst rubble of his shop. The people of Kachchh are known for being tough and resilient. His beautiful smile despite the circumstances gives hope for the future. (Photo by Sudhir K. Jain)*

Concluding Remarks

The Bhuj earthquake is the first major earthquake to strike an urban region in India, and the biggest earthquake disaster in recent Indian history. The earthquake has brought to focus some important issues regarding earthquake risk reduction:

1. The numerous casualties are a direct result of the fact that most construction in the region did not comply with the seismic building code provisions, partly because the codes are not mandatory and partly due to lack of professionalism among structural engineers. The situation is no different in most other parts of India and these issues need to be addressed urgently.

2. Many RC moment-resisting frame buildings with soft first stories for parking sustained serious structural damage and caused numerous deaths. Since this building system is common in most parts of India, it has created widespread concerns. This is the right time to initiate serious efforts to evaluate this building system and develop retrofit methodologies.

3. Numerous RC frame buildings not designed for lateral forces withstood the earthquake shaking due to the beneficial presence of masonry infills. Masonry infills contribute a significant amount of stiffness and strength and can be an asset rather than a liability provided a) their placements do not cause configuration irregularities, and b) the length and height of the infills are limited to avoid out-of-plane collapses. Such buildings will continue to be built in India and in many other developing countries, so there is an urgent need to develop design methodologies for such systems in seismic regions.
4. Numerous collapses and deaths in Ahmedabad and other urban areas have once again highlighted the risk to major Indian cities from future great earthquakes along the Himalayan frontal fault system. Nonstructural damage to a few buildings in New Delhi caused by the M6.6 Chamoli (India) earthquake of 1999, with epicentral distance of 280km, had clearly pointed out this possibility.

5. A number of earth dams in the region were seriously damaged. Fortunately, all these dams had low water level following several years of drought, but this emphasized the need for seismic evaluation and retrofit of dams in high seismic regions. Moreover, the earthquake has provided excellent case histories for a better understanding of the seismic behavior of earth dams.

6. This earthquake occurred in an area known for high seismic vulnerability, and yet, appropriate emergency response plans to handle such an eventuality had not been developed.

7. Immediately after the earthquake, a need arose for a large number of structural engineers with expertise in earthquake-resistant structures. This need could not be adequately met with the very few such engineers even in a highly populated country like India. There is an urgent need to begin a serious human resource development initiative in this discipline in India.

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