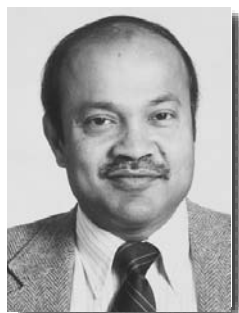


Observations From the Bhuj Earthquake of January 26, 2001



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The devastating earthquake that struck the Kutch area of Gujarat, India on January 26, 2001, India's Republic Day, was the most severe natural disaster to afflict India since her independence in 1947. The devastation was major in terms of lives lost, injuries suffered, people rendered homeless, as well as economics. The author visited the affected areas between February 12 and 16, 2001, as a member of a reconnaissance team that was organized by the Mid-America Earthquake Center based at the University of Illinois at Urbana-Champaign and funded by the National Science Foundation. This report is based partly on his first-hand observations from that visit and partly on information gathered from several sources, including other visiting teams, news reports and technical literature. The author touches upon seismological/geotechnical aspects of the earthquake and discusses the performance of engineered buildings. Bridges, non-engineered buildings and other structures are excluded from the scope. Precast concrete construction, including non-building uses of precast concrete, is discussed. In concluding the article, the building code situation in India is briefly commented upon.

The Bhuj earthquake of January 26, 2001 struck at 8:46 a.m. Indian Standard time and had a Richter magnitude of 7.7 (United States Geological Survey, revised from an initial estimate of 7.8). The epicenter was located at 23.36°N and 70.34°E, less than 30 miles (50 km) to the northeast of Bhuj, an old, walled city with a population of 160,000 (see map, Fig. 1).

Although the official death toll never exceeded 35,000, unofficial estimates of casualties have ranged from 100,000 to 150,000. Conservative estimates of economic losses suffered stand at 5 billion U.S. dollars.

SEISMOLOGICAL AND GEOTECHNICAL ASPECTS

According to a press release issued by the Mid-America Earthquake Center, the India earthquake provided a mirror

image of the geology and earthquake history of the New Madrid earthquakes of 1811 and 1812, the largest earthquakes to occur in the U.S. continental 48 states, even greater than the 1906 San Francisco earthquake. Researching the geophysics and related damage of this earthquake was considered a once-in-a-lifetime learning opportunity to better prepare Mid-America for a future repeat of the New Madrid earthquake. This Gujarat earthquake was considered to be the largest intraplate earthquake, not associated with a subduction zone, since the 1811-1812 events.

The India earthquake was felt to have very important implications for the nature of ground motion in the foreseeable next major New Madrid earthquake and how our infrastructure will respond, since both events involve intraplate faults having very large magnitudes and long attenuation distances. However, according to some seismologists,¹ the tectonic setting of the Kutch region is not well understood. It has been

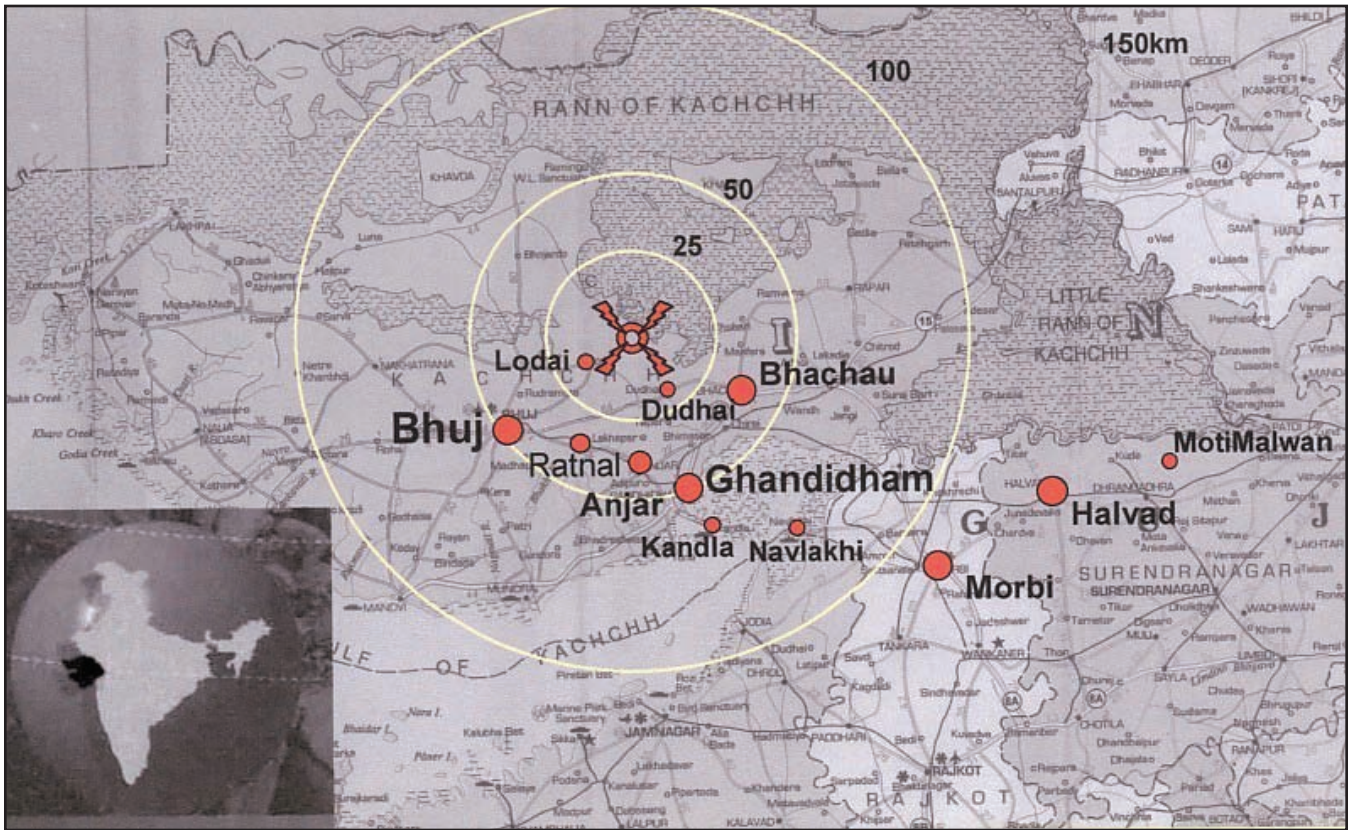


Fig. 1. Map of earthquake-affected area. Courtesy: MAE Center.

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.

Earthquakes, of course, are not unknown in India. Fig. 2 shows the epicenters of earthquakes of Richter magnitude 6.0 and higher that have occurred in the short time span between 1964 and 2001. Table 1 provides a list of significant earthquakes occurring since 1819.

The land of Kutch, Gujarat was struck by a massive earthquake at 6:45 p.m. on June 16, 1819. Captain McMerdo, a British agent stationed at Anjar at that time, described the devastating aftermath of the earthquake in a letter that has resurfaced since the recent earthquake. In many respects, including seismological and geotechnical, the January 26, 2001 earthquake was a case of history repeating itself 182 years later.

Captain McMerdo described in his letter how the ground water level rose in most places and how the underground water turned sweet in areas

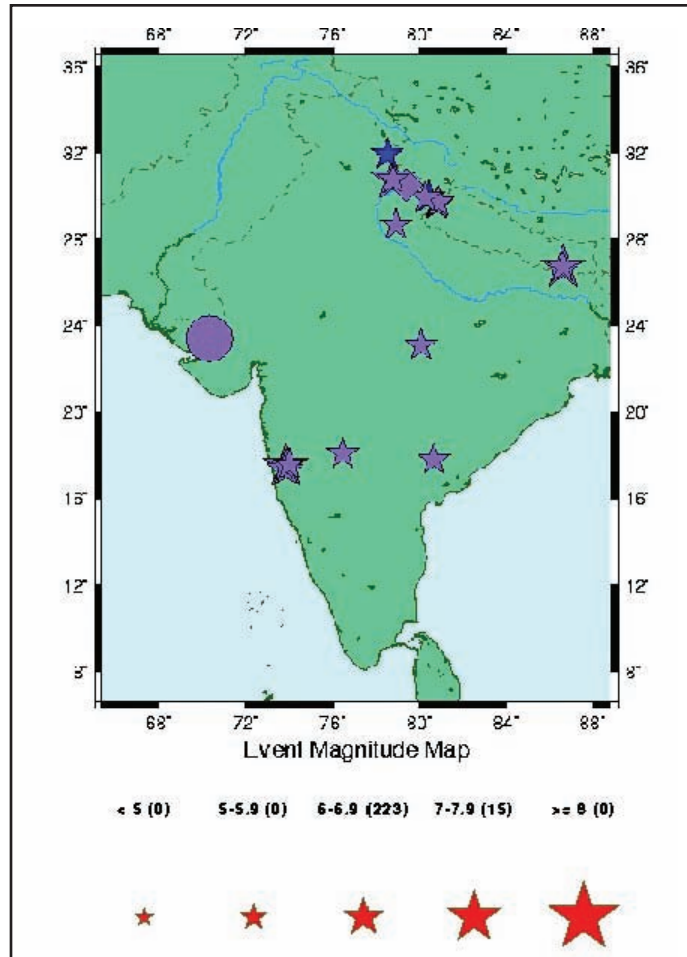


Fig. 2. Map of India showing epicenter of recent earthquakes.

where it was salty earlier. He also mentioned fissures in the earth, and of the Indus river changing its course.

On February 14, almost 3 weeks after the Bhuj earthquake, ground water was observed to be bubbling out at one location near the village of Lodi. There were reports from that and other locations of geysers, several feet tall, erupting after the earthquake. The groundwater coming up near Lodi was sweet, as evidenced by algae growing on already accumulated water, whereas the groundwater in that part of Gujarat is typically salty. Ground failure and liquefaction were quite widespread (see Figs. 3 and 4).

PERFORMANCE OF ENGINEERED BUILDINGS

Performance of engineered construction was investigated by the Mid-America Earthquake (MAE) Center team in Ahmedabad, Morbi, Gandhidham, Bhuj and Bhachau, located approximately 155, 71, 31, 30, and 19 miles (250, 115, 50, 48, and 30 km) away from the epicenter, respectively.

Ahmedabad

The only strong motion instrument in the entire area affected by the Bhuj earthquake was in the basement of a multi-story building in Ahmedabad, approximately 155 miles (250 km) away from the epicenter. The recorded peak ground acceleration was 0.1g (see Fig. 5).

Ground motion of this intensity should not cause significant structural damage to properly engineered construction. Yet more than 70 multistory residential buildings collapsed in Ahmedabad. The reasons for such disproportionate damage were fairly apparent.

Building Period Versus Ground Motion Period – Short-period components of ground motion typically die out faster than the long-period components of ground motion as earthquake shocks travel away from the source of an earthquake. Typically, at long distances away from the epicenter, the ground motion has predominantly long-period components.

From the copy available to the MAE Center team of the sole ground motion record, it was not possible to discern

Table 1. Major earthquakes in India.

Date	Location	Scale
June 16, 1819	Kutch, Gujarat	8.0
January 10, 1869	Cachar, Assam	7.5
May 30, 1885	Sopor, Kashmir	7.0
June 12, 1897	Shillong Plateau	8.7
April 4, 1905	Kangra, Himachal	8.0
July 8, 1918	Srimangal, Assam	7.6
July 2, 1930	Dhubri, Assam	7.1
January 15, 1934	North Bihar	8.3
June 26, 1941	Andaman Islands	8.1
October 23, 1943	Assam	7.2
August 15, 1950	Arunachal Pradesh	8.5
July 21, 1956	Anjar, Gujarat	7.0
December 10, 1967	Koyna, Maharashtra	6.5
January 19, 1975	Kinnaur, Himachal	6.2
August 6, 1988	Manipur	6.6
August 21, 1988	North Bihar	6.4
October 20, 1991	Uttar Pradesh Hills	6.6
September 30, 1993	Latur, Maharashtra	6.3
May 22, 1997	Jabalpur, M.P.	6.0

Source: Indian Meteorological Department.

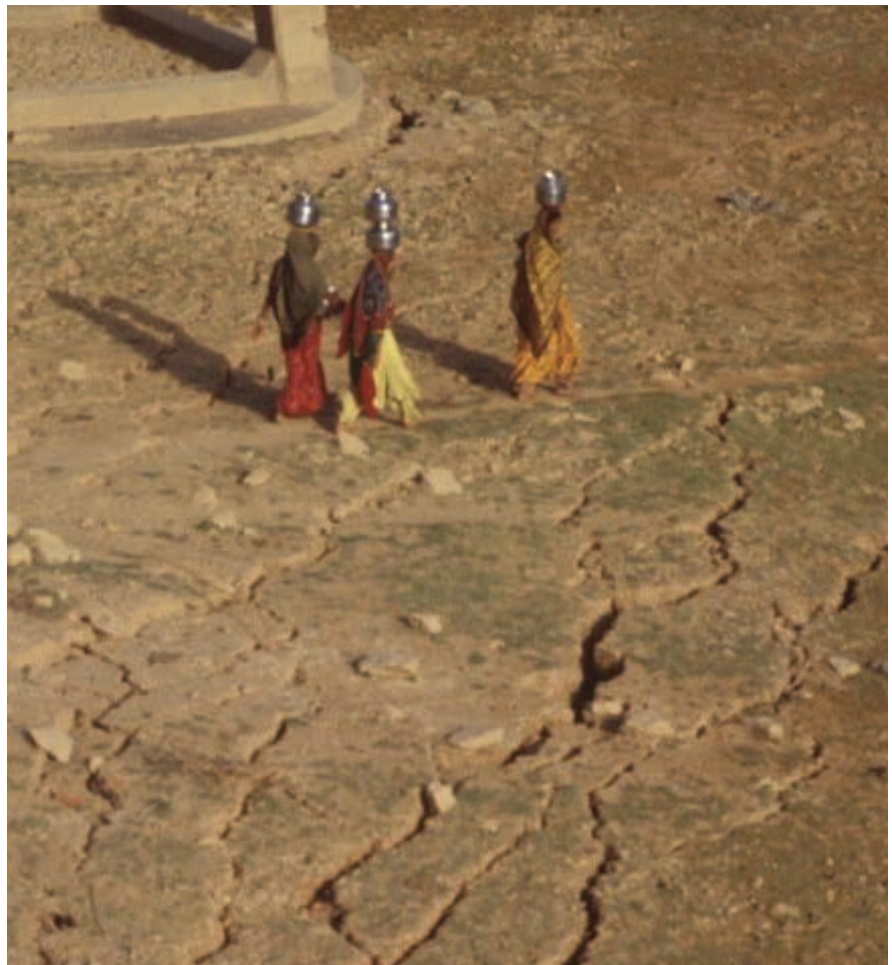


Fig. 3. Ground failure caused by earthquake. Courtesy: MAE Center.



Fig. 4. Liquefaction caused by earthquake. Courtesy: MAE Center.

the predominant period. However, it would be safe to speculate that the predominant periods were 0.5 second and longer. This in itself would explain the lack of damage to shorter buildings in Ahmedabad.

The buildings that collapsed were in the ground plus four to ground plus ten-story height range. Buildings in this height range, particularly considering the type of construction, most likely had elastic fundamental periods in the range of the predominant periods of the ground motion. The consequent near-resonant response must have been, at least in part, responsible for much of the damage sustained.

Soft Soil – Goel² has made an important observation with respect to the soils on which the collapsed Ahmedabad buildings were founded. According to him, “Although a cursory analysis of location of building collapses would indicate no particular pattern, a careful analysis reveals that most of the buildings that collapsed lie along the old path of Sabarmati River...Note that the path of most of the buildings that collapsed in areas west of the Sabarmati River are closely aligned with the old path of the river...just west of the present river path. The south, southeast of the city, especially the Mani Nagar area, where additional

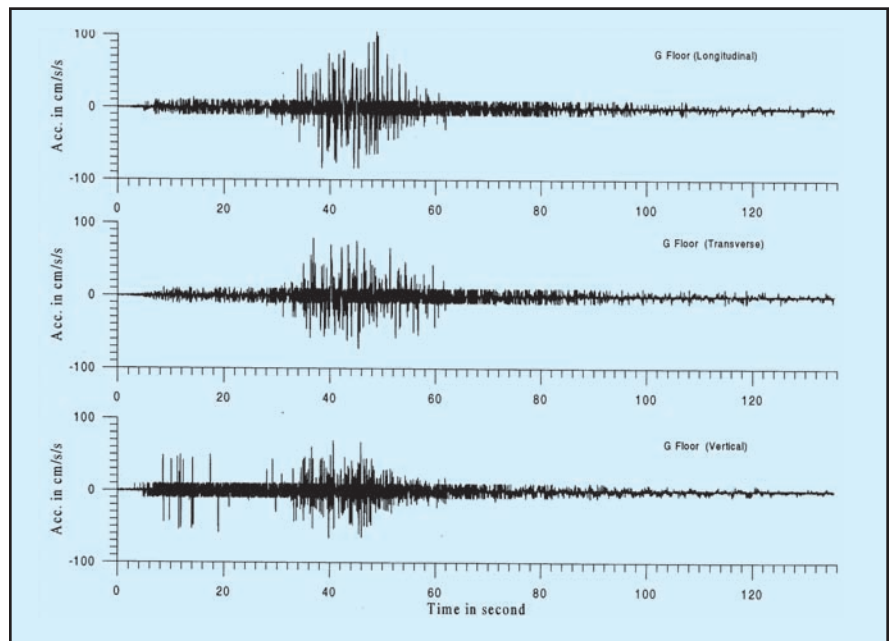


Fig. 5. Accelerogram recorded at basement of a building in downtown Ahmedabad.

collapses were observed, falls between two lakes, indicating the presence of either poor soil conditions or possibly construction on non-engineered fills. While the evidence presented...is strong, it would be useful to further verify these conclusions with field testing.”

Type of Construction – Multistory residential buildings (and most other multistory buildings) in Ahmedabad,

the rest of India, and indeed in much of the world, are constructed of reinforced concrete frames, with the openings in those frames infilled with unreinforced clay brick masonry.

There is a problem inherent in the use of unreinforced masonry infills. Initially, while they are intact, they impart significant stiffness to a building which, as a consequence, attracts strong earthquake forces. The resulting

deformations are often more than sufficient to cause cracking or even explosive failure of the infilled masonry. When that happens, the period of the building lengthens significantly all of a sudden.

Although this usually is beneficial in terms of attracting less earthquake forces, depending on the nature of the earthquake ground motion, the opposite may be the case. For example, in the 1985 Mexico earthquake, with the predominant 2-second period of the ground motion in downtown Mexico City, a building attracted stronger earthquake forces with the loss of the infill. Also, very importantly, the altered earthquake forces must be resisted essentially by the bare frame. If the frame lacks that capability, severe damage or collapse may result.

Stiffness Discontinuity or Soft Story – In virtually all Indian cities, the multi-story residential buildings of the type described above have open ground stories for parking of automobiles, because the small lots on which such buildings are typically built do not allow for open parking (see Fig. 6). This means an almost total absence of infills at the ground level, thus creating a very distinct stiffness discontinuity or a soft story.

Virtually all the earthquake-induced deformations in such a building occur in the columns of the soft story, with the rest of the building basically swaying uncontrollably. If these columns are not designed to accommodate the large deformations, they may fail, leading to a catastrophic failure of the entire building, as was the case with many buildings in Ahmedabad and elsewhere.

Discontinuity of Vertical Load Path – The local municipal corporation in Ahmedabad imposes a Floor Surface Index (FSI), which restricts the ground floor area of a building to be no more than a certain percentage of the lot area. It is, however, permitted to cover more area at the upper floor levels than at the ground floor level. The same is the situation in many other Indian cities as well. Thus, most buildings have overhanging covered floor areas at upper floors, with overhangs frequently ranging up to 5 ft (1.52 m) or more.

The columns on the periphery of the upper floors do not continue down to the ground level. The columns at the ground floor level also may or may not align with the columns at the upper levels. Significant vertical discontinuities are, therefore, generated in the lateral-force-resisting system.

Non-Ductile Detailing – Goel² has reported: “The columns for low-rise residential buildings, up to ground plus four stories (G + 4), rest on shallow isolated footings located about 5 ft (1.52 m) below the ground level. For taller buildings, say up to ground plus ten stories (G + 10), the column foundations are still open footings located at a depth of 8 to 10 ft (2.44 to 3.05 m); sometimes the foundation may also have tie beams. The column sizes for low-rise buildings (G + 4) are about 9 x 18 in. (230 x 460 mm) with ties consisting of smooth No. 2 mild steel bars at a spacing of about 8 to 9 in. (200 to 230 mm). The beams tend to be much deeper to accommodate large spans and overhangs, giving rise to strong beam-weak column construction. The column sizes for taller buildings tend to be a little bigger, usually 12 x 24 in. (300 x 600 mm) with No. 3

deformed steel ties at a spacing of 8 to 9 in. (200 to 230 mm). The beam size in taller buildings may be similar to the column size. These ties always end up with 90-degree hooks.”

Such non-ductile detailing of reinforced concrete construction is common practice around the world, including pre-1973 reinforced concrete construction in California, although details vary from place to place and depend upon the age of the building. In addition to all of the above, column reinforcement is typically spliced right above the floor levels; splice length in the columns as well as the beams is often insufficient; and continuity of beam reinforcement over and into the supports is often also insufficient.

The large deformations that take place in soft story columns also impose extreme shear demands on them. The meager lateral reinforcement described above not only provides poor confinement; the shear strength available is also quite low. As a result, many ground floor columns failed in a brittle shear mode, or in a combined shear plus compression mode, bringing down the supported buildings (see Fig. 7). Many times, in columns that had



Fig. 6. Typical soft-story residential building. Courtesy: Tiziana Rossetto, Imperial College, London.

not failed, diagonal shear cracking was evident (see Fig. 8).

Torsion – The typical soft-story residential building described above is torsionally quite flexible at the ground floor level. If appreciable eccentricities between the center of mass and the center of rigidity are introduced because of asymmetric placement of walls or other reasons, significant torsional motions may result. These may subject columns on one side of a building to excessive deformations. If not adequately designed to accommodate such deformations, the columns may fail, contributing to building collapse. According to Goel,² “deformations due to torsion may have contributed to failure of at least one building” in Ahmedabad.

Detailing of Shear Wall Core and Connection to Remainder of Structure –

The typical soft-story residential building described above relies upon the shear wall core(s) around stairwell(s) and/or elevator shafts to resist most of the lateral load at the ground floor level. Up the height of the building, the shear walls do unload increasing percentages of story shears onto the



Fig. 7. Non-ductile detailing of column. Courtesy: MAE Center.

frames, provided the floor diaphragms connecting them are rigid enough in-plane to impose equal displacements on the shear walls and the frames. Several deficiencies were observed.

The ratio of cross-sectional area of shear walls to plan area of building

was often quite low. The shear walls are typically about 4 to 6 in. (100 to 150 mm) thick with very light reinforcement consisting of two layers of mesh formed with No. 3 or No. 4 bars at vertical and horizontal spacings of about 18 in. (460 mm).

Such detailing was often insufficient to resist the lateral loads at the ground floor level; severe shear cracking of shear walls at the ground level was frequently observed. The shear cracking often did not extend above the ground floor level, reflecting reduced shear demand on the walls.

The shear wall core was often connected to the rest of the building only through the floor slabs, with no beams framing into the shear walls. The anchorage of slab reinforcement into the elevator core was often insufficient. As a result, the shear walls sometimes just pulled out from portions of the building, leaving them devoid of much lateral resistance.

Material Quality – There were indications that deficient material quality might also have contributed to structural damage, or even collapse. Goel, in his recent paper,² showed the bottom of a column in a partially collapsed building. “The concrete has simply disintegrated within the reinforcement cage, when touched, the concrete felt sandy with little cement. Also, note that the 90-degree hooks have opened up, which leads to little



Fig. 8. Shear cracking of column. Courtesy: MAE Center.



Fig. 9. Ground level column punching through floor slab of a building.

or no confinement of the concrete. Many times, the concrete cover to reinforcement was noted to be less than 0.5 in. (13 mm), where most of the cover was provided by the plaster used to smooth the column surface. It is worth noting that most of the water supply in the outer part of the city is through ground water which is salty in taste. Usually, the same water is used in preparing the concrete for construction. Therefore, the presence

of salts may have also affected the concrete quality.”

Other Cities

Observation of the performance of engineered buildings in four other cities – Morbi, Gandhidham, Bhuj and Bhachau – did not produce substantially new technical information. As the epicentral distance decreased, even relatively short buildings were not spared.

In Gandhidham, there was an inter-

esting case of several ground-story columns in a building (in which the soft ground story had collapsed) having punched through the first suspended slab (see Fig. 9).

In another case, the shear core of a building had completely separated from the rest of the building (see Fig. 10). The right wing of the building had collapsed. The left wing was still standing up.

Finally, in Bhuj, one example of a very few overturned buildings was observed (see Fig. 11).

PRECAST CONSTRUCTION

According to an Earthquake Engineering Research Institute (EERI) Special Earthquake Report,¹ some single-story school buildings in the Kutch region are made of large-panel precast reinforced concrete components for the slabs and walls, and precast reinforced concrete columns. The EERI report indicates that a typical design using this construction has been recently replicated all over Gujarat, including the earthquake-affected region. The report also indicates that approximately one-third of 318 such schools in the Kutch region had roof collapses.

Inadequate connection between the roof panels led to a lack of floor-diaphragm action, and insufficient seating and anchorage of the roof panels over the walls and beams led to dislodgment of the precast roof panels from the tops of the walls. These phenomena have been observed in many past earthquakes across the world. The author did not have the opportunity to observe the performance of any of these precast schools first-hand.

Precast concrete has found fairly popular use in railroad ties (sleepers). The railroad network in the affected area was closed for inspection immediately following the earthquake. It turned out that there was surprisingly little damage to the network. It was made operational up to Gandhidham on January 29.

The Gandhidham to Bhuj railway segment was closed at the time of the earthquake for gauge conversion (narrow gauge to broad gauge) and was scheduled to become operational on January 31. This segment became op-



Fig. 10. Core separated from rest of building.

erational on February 3. Fig. 12 shows precast sleepers supporting the new broad-gauge railway track near Morbi.

Precast concrete also is used in a limited way in utility poles and fence poles. In cities such as Bhuj, there was damage to many of these poles, as would be expected. However, there was also damage to metal poles.

INDIAN CODES AND STANDARDS

India has, for quite some time now, had sophisticated codes and standards. The three documents relevant to this discussion are:

1. **IS1893:1984** – Indian Standard Criteria for Earthquake Resistant Design of Structures (Fourth Revision).
2. **IS 4326:1993** – Indian Standard Earthquake Resistant Design and Construction of Buildings – Code of Practice.
3. **IS 13920:1993** – Indian Standard Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces – Code of Practice.

IS 1893 states: “It is not intended in this standard to lay down regulations so that no structure shall suffer any damage during earthquakes of all magnitudes. It has been endeavored to ensure that, as far as possible, structures are able to respond, without structural damage to shocks of moderate intensities, and without total collapse to shocks of heavy intensities.”

IS 1893 contains a seismic zoning map. The object of this map is to classify the area of the country into a number of zones in which one may reasonably expect earthquake shock of more or less the same intensity in the future. The modified Mercalli Intensity associated with the various zones is V or less, VI, VII, VIII, and IX and above for Zones I, II, III, IV, and V, respectively.

It may be noted that Bhuj is in Seismic Zone V, while both Ahmedabad and Mumbai (Bombay) are in Zone III.

IS 4326 is intended to cover the specified features of design and construction for earthquake resistance of buildings of conventional types. In the case of other buildings, detailed analy-



Fig. 11. Overturned building.

sis of earthquake forces is required. Recommendations regarding restrictions on openings, provision of steel in various horizontal bands and vertical steel in corners and junctions in walls and at jambs of openings are based on extensive analytical work. Many of the provisions have also been verified experimentally on models by shake table tests.

IS 4326: 1976 “Code of Practice for Earthquake Resistant Design and Con-

struction of Buildings,” while covering certain special features for the design and construction of earthquake resistant buildings, included some details for achieving ductility in reinforced concrete buildings. With a view to keeping abreast of the rapid developments and extensive research in the field of earthquake resistant design of reinforced concrete structures, the decision was made to cover provisions for the earthquake resistant design and



Fig. 12. Precast railroad ties (sleepers).

detailing of reinforced concrete structures separately.

IS 13920 incorporates a number of important provisions not covered in IS 4326:

- (a) As a result of the experience gained from the performance in earthquakes of reinforced concrete structures that were designed and detailed according to IS 4326: 1976, many identified deficiencies were corrected in IS 13920.
- (b) Provisions on detailing of beams and columns were revised with the aim of providing them with adequate toughness and ductility so as to make them capable of undergoing extensive inelastic deformations and dissipating seismic energy in a stable manner.
- (c) Specifications on seismic design and detailing of reinforced concrete shear walls were included.

The other significant items incorporated in IS 13920 are as follows:

- (a) Material specifications are indicated for lateral-force-resisting elements of frames.
- (b) Geometric constraints are imposed on the cross section for flexural members. Provisions on minimum and maximum reinforcement have been revised. The requirements for detailing of longitudinal reinforcement in beams at joint faces, and splices and anchorage requirements are made more explicit. Provisions are also included for the calculation of design shear force and for detailing of transverse reinforcement in beams.
- (c) For members subjected to axial load and flexure, dimensional constraints have been imposed on the cross section. Provisions are included for detailing of lap splices and for the calculation of design shear force. A comprehensive set

of requirements is included on the provision of special confining reinforcement in those regions of a column that are expected to undergo cyclic inelastic deformations during a severe earthquake.

- (d) Provisions have been included for estimating the shear strength and flexural strength of shear wall sections. Provisions are also given for detailing of reinforcement in the wall web, boundary elements, coupling beams, around openings, at construction joints, and for the development, splicing and anchorage of reinforcement.

While the common methods of design and construction have been covered in IS 13920, special systems of design and construction of any plain or reinforced concrete structure not covered by that code may be permitted on production of satisfactory evidence, regarding their adequacy for seismic performance by analysis, or tests, or both.

It is interesting to note that the provisions of IS 13920 apply to reinforced concrete structures that satisfy one of the following conditions:

- (a) The structure is located in Seismic Zone IV or V;
- (b) The structure is located in Seismic Zone III and has an importance factor greater than 1.0;
- (c) The structure is located in Seismic Zone III and is an industrial structure; and
- (d) The structure is located in Seismic Zone III and is more than five stories high.

Thus, the residential buildings in Ahmedabad with ground plus four stories are exempt from the requirements of IS 13920.

The above codes, as noted earlier, are quite sophisticated. IS 13920:1993 is, in fact, greatly influenced by ACI

318-89. However, code enforcement practically does not exist in India.

Central and State governments would at times require code compliance for buildings owned by them. For other buildings, code requirements are seldom, if ever, enforced. Local jurisdictions typically do not have a mechanism in place to enforce code requirements. This not only explains much of the damage observed to engineered buildings, but also indicates that the promise of a bright new future is not on the horizon.

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