A National Technological Crisis

Structural and Geotechnical Damages Sustained During M7.9 Bhuj Earthquake Force

C. V. R. Murty, Umesh Dayal, Jaswant N. Arlekar, Sailender K. Chaubey, and Sudhir K. Jain
Department of Civil Engineering, Indian Institute of Technology, Kanpur.

The powerful earthquake that struck the Kutch area in Gujarat at 8:46 am on 26 January 2001 has been the most damaging earthquake in the last five decades in India. The M7.9 earthquake was centered near Bhuj and was felt in most parts of the country. About 20 districts in the state of Gujarat sustained damage. The entire Kutch region of Gujarat, enclosed on three sides by the Great Runn of Kutch, the Little Runn of Kutch and the Arabian Sea, sustained highest damage with maximum intensity of shaking as much as X on the MSK intensity scale. The strong motion records obtained at the Passport Office Building under construction in Ahmedabad city (~300km east of Bhuj) indicate a peak ground acceleration of about 0.11g.

Several towns and large villages, like Bhuj, Anjaar, Vondh and Bhachau, sustained widespread destruction (Figure 1). The other prominent failures in the Kutch region include extensive liquefaction, failure of several earth dams of up to about 20m height, damage to masonry arch and RC bridges, and failure of railroad and highway embankments. Numerous recently-built multi-storey RC frame buildings collapsed in Gandhidham and Bhuj in the Kutch region, and in the more distant towns of Ahmedabad (300km east) and Surat (375km southeast) killing a large number of people (Figure 2).

The state of Gujarat is the heartland of Indian industries like petroleum, power and steel. Indeed, this M7.9 earthquake is the first to hit metropolitan cities and the modern industrial constructions of the country in the recent times. Therefore, the performance of structures in this area offer important lessons particularly from the points of view of efficacy of Indian construction practices. Experiences from here would serve as an excellent evidence for the Indian civil engineering community on the performance of its own traditional and modern constructions.

Figure 1: Total collapse of traditional houses in random rubble stone masonry with mud mortar at Maliya village.

The following provides a quick field report of the salient structural and geotechnical damages observed during a reconnaissance survey to capture important lessons from the aftermath of the quake, conducted during 02-14 February 2001 by a team of 15 investigators jointly headed by Professor Sudhir K. Jain of the Department of Civil Engineering, Indian Institute of Technology Kanpur, and Dr. William Lettis of William Lettis & Associates, Inc, USA. The investigators included geologists, seis-

Figure 2: Collapse of the ground storey and vertical splitting of a typical four-storey RC frame building.

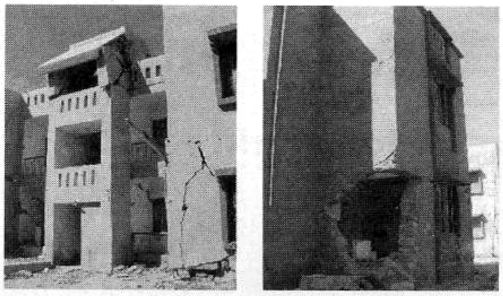

Figure 3: Imminent collapse of staircase tower and collapse of the corner of two-storey large block stone masonry houses without lintel bands in Bhuj.

Figure 4: Precariously balanced severely damaged RC frame building with open ground storey in Ahmedabad.

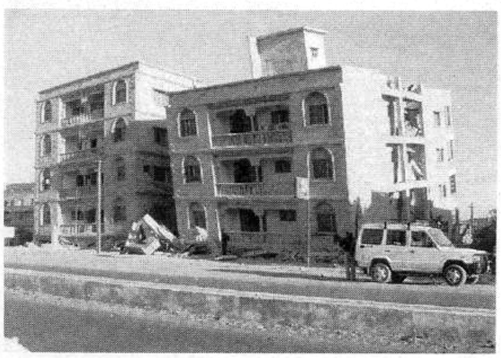

Figure 5: Ground storey collapse of a 4-storey building with open ground storey at Bhuj.

mologists, geophysicists, geotechnical engineers, structural engineers, and emergency managers. The Earthquake Engineering Research Institute (EERI), Department of Science and Technology (Government of India), New Delhi, and Indian Institute of Technology Kanpur supported the investigation.

Building Systems

The buildings in the affected area can be placed in two broad groups:

- The older non-engineered dwellings with load-bearing masonry walls supporting tiled roof or RC slab roof. The different types of masonry consisted of random rubble stone with mud/cement mortar, small/large block cut stone in mud/cement mortar, clay bricks in mud/cement mortar, and hollow/solid cement blocks in cement mortar.
- The newer reinforced concrete frame buildings with unreinforced masonry infill. The infills were of varied type, namely clay brick masonry in cement mortar, small/large block cut stone masonry in cement mortar, and hollow/solid cement blocks in cement mortar.

In the former type, the damages are owing to ills of masonry similar to that extensively experienced in the aftermath of some of the recent Indian earthquakes. The problems of walls not being adequately connected to each other and to the roof, separation of the 40-60cm thick masonry walls into two distinct wythes, and failure of the rather heavy mass "Mangalore" clay tile roofing system with thick wooden logs as purlins and rafters, are among the notable deficiencies of such dwellings. The Kutch area has additional characteristic constructional issues associated with the non-engineered constructions. For instance, the use of very large block (25cm´40cm´60cm) masonry with mud mortar or low strength cement mortar is very common (Figure 3). These too have shown very poor performance.

Among the cities affected in the area are two densely populated metropolitan cities of Ahmedabad and Gandhidham, where many modern reinforced concrete multi-storey buildings have collapsed. Amongst the multistorey buildings that collapsed, most had the ground storey left open for parking convenience with few or no filler walls between the columns (Figure 4). This created a top stiff inverted pendulum structure. This coupled with insufficient strength and stiffness of the RC columns in the open ground storey rendered the buildings vulnerable (Figure 5). Most buildings with complete infill in the ground storey have withstood the earthquake without collapse. This feature of infilled frames is very important for India and many other developing countries wherein seismic design is not conducted for most buildings and wherein unreinforced masonry infill are extensively used as "non-structural" components. The design of new buildings and seismic retrofit of existing constructions should account for the beneficial effects of the masonry filler walls considering their strength and stiffness.

The area has a number of about 30 single-storey school buildings built recently with large panel RC precast roof and wall elements and precast RC columns. Of these, many are reportedly damaged; at least two of these are known to have collapsed (Figure 6). As experienced in past earthquakes across the world, the insufficient connections between the roof panels to generate the floor diaphragm action, and the inadequate connections between the roof panels and the vertical elements, led to the collapses. Precast technologies have not been very popular in India. Particularly, their suitability in high seismic areas has not yet been established experimentally. Thus, a serious need arises to re-look at the feasibility of such constructions before anymore such constructions are employed in seismic areas and that too as school buildings.

Bridges

The area affected by the earthquake had a large number of railway and highway bridges. Most of them sustained damage though to varying extents. The multi-span bridges indicated pounding of the adjoining simply supported spans at the deck level, lateral movement of the superstructure decks and the consequent damage to bearings, and distress to the masonry arches and piers. In short bridges, damage to the abutment wing walls, slumping of the approach embankments and severe damage to the RC/masonry piers were also experienced. A number of RC slab culverts on stone masonry abutments sustained damage at the seating of the span. The poor configuration of the superstructure decks in multi-span bridges, *i.e.*, adjacent spans with unequal-height bed blocks owing to the two spans having girder/slab with different depths, was very obvious from the severe damage sustained by one such bridge in the epicentral area (Figure 7). This is a very good lesson for future to avoid such designs.

The only road link between the Kutch and Saurashtra areas is the old road bridge at Surajbadi, which is a multi-span balanced cantilever RC Slab Bridge with suspended spans. This bridge sustained severe damage at the bearings at most piers, and its deck moved laterally at one of the piers in the transverse direction. This stalled traffic for a few days before it was temporarily restored for slow traffic conditions. At the same location, there is a new multi-span bridge under construction that was provided with RC upstands at the ends of the pier caps to act as restrainers to prevent the transverse motion of the superstructure. Most of these restrainers were damaged indi-

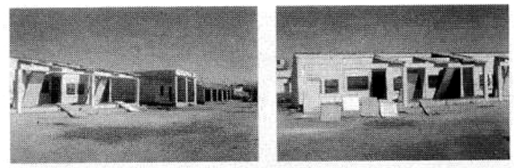

Figure 6: A school in Gandhidham had both traditional construction as well as RC precast buildings. In the precast building, the roof panels were dislodged atop the precast frame/wall system due to inadequate connections. In contrast, the traditional constructions alongside did better.

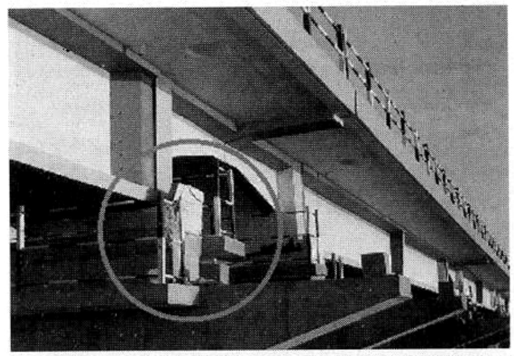

Figure 7: The bridge was provided with RC lateral restrainers to prevent dislodging of spans in the transverse direction. Most of these devices sustained damage due to lateral pounding by the spans.

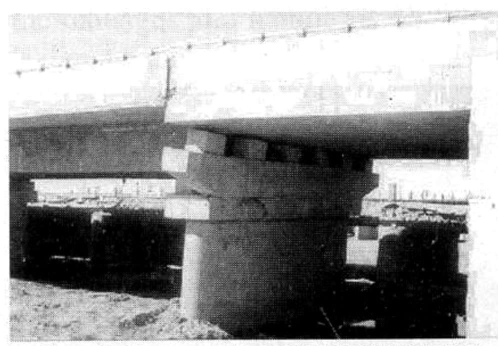

Figure 8: Damage to the unequal-height bed blocks at the RC bridge near Vondh. The pier supports two spans with different girder/slab depths.

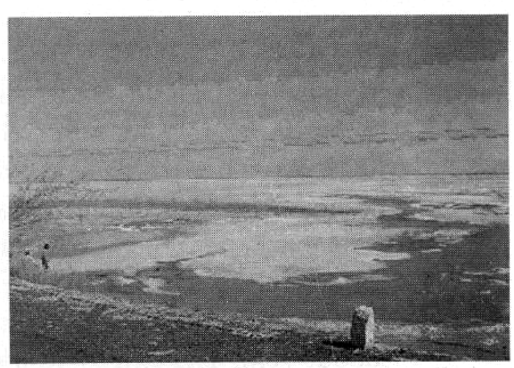

Figure 9: Extensive liquefaction near India Bridge at Khawda (The Great Runn of Kutch).

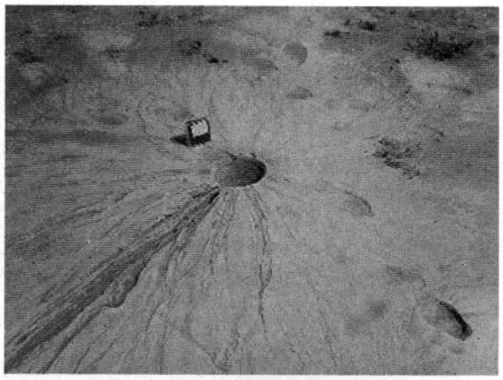

Figure 10: One typical sand boil (6-8m in diameter and 20cm in height) from the liquefied area in the Great Runn of Kutch.

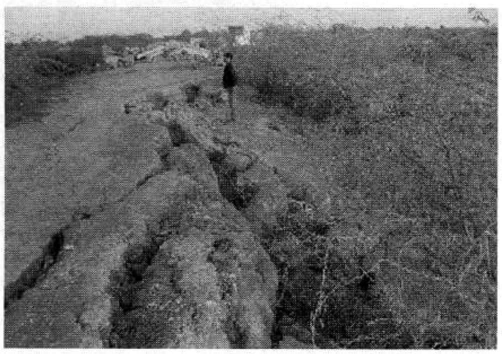

Figure 11: Failure of the upstream slope of the Fatehgad dam.

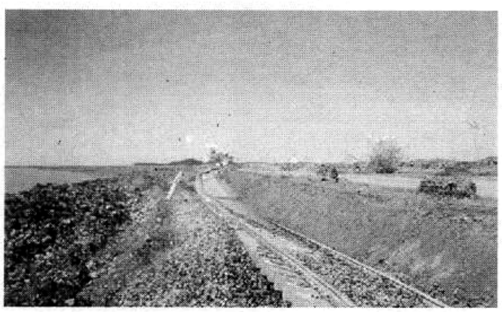

Figure 12: Massive slope failure of the rail-road embankment near Navlakhi port resulting in fracture of rails, and damage to prestressed concrete sleepers and panroll clips.

cating their successful use (Figure 8). The large movement of the girders of this bridge along the longitudinal and transverse directions imposed severe strains on the neoprene bearings. The possible uplift of the girders may have also been responsible for the spalling of cover concrete at the bottom of the girders.

Geotechnical Damages

The earthquake provided excellent examples of large-scale liquefaction and embankment failures. The Great Runn of Kutch, the Arabian Sea and the Little Runn of Kutch lock the affected area on its three sides. This enclosed area at near sea level suffered extensive liquefaction, a phenomenon of quicksand condition by virtue of which the soil looses the capacity to hold structures in place (Figure 9). Classic sand boils (6-8m in diameter and 20cm in height) are captured from the liquefied area that had an impervious overlying layer (Figure 10). But, at many other locations, liquefaction was widespread. The extensive liquefaction under a 3-storey RC frame office building at Kandla port caused only minor cracks in the walls. However, the building settled down by about 7cm. The extensive liquefaction in the Runn of Kutch did not affect the performance of the numerous high-tension transmission lines in the area, which were founded on pile foundations with a rigid pile cap. In the epicentral area, extensive liquefaction at Amarsar also caused lateral spreading of the ground up to about a meter.

At least five earth dams (Tappar, Kaswati, Fatehgad, Rudramata and Suvi) have failed during this earthquake (e.g., Figure 11). The damage included slope failures of the upstream/downstream side, longitudinal cracks along the crest of the dam, vertical settlement of the embankment in general, and toe failures on the upstream side. This is a very serious matter particularly with the impending rainy season. Also, the failure of a large number of dams during one single earthquake has generated tremendous interest in the international scientific community to benchmark their analytical models using these failures; some at-site tests/investigations may be required to assess the soil parameters at these sites. Failure of sea wall at Navlakhi port, wherein over 50 meters stretch of the wall was washed away into the sea, provided yet another example of the catastrophic soil slope failures.

The earthen embankments of the railroad and highways also suffered widespread damage. The massive slope failure of the rail-road embankment near Navlakhi port resulting in fracture of rails, and damage to prestressed concrete sleepers and panroll clips, should stand as the main source deterrent to looking away from the concerns related to geotechnical problems (Figure 12). In some instances, ground liquefaction at the base of the embankment was responsible for extensive damages to the railway embankments. Damage to highway pavement and kerbs due to lateral spreading of soil, and approach embankments have been reported from the entire epicentral area. It is clear that a greater emphasis than now is required to the design of geotechnical components of the railway and highway projects.

Industrial and Other Structures

The wharf, the industrial warehouses and the control tower buildings at the port of Kandla suffered major damages owing to both structural inadequacies as well as liquefaction of the ground. The lateral spreading of the liquefied soil at the jetty, led to a lateral translation of the 50cm diameter piles of the old jetty, resulting in flexural cracking in them (Figure 13). However, the 100cm diameter piles under the newer jetty performed well. The flexural and shear cracks at the beam-column joint at the knee-bent frame supporting craft jetty; severe damage (cyclic shear cracks) to the exterior short columns at the ventilators of the warehouse in the form of opening of ties and buckling of longitudinal steel; undulations of floor tiles of the container terminal due to extensive liquefaction; and a 15° tilt in the six-storey control tower structure on the shores due to liquefaction of the underlying soil and consequent lateral spreading towards the bay, are some of the notable damages at the Kandla port (Figure 14).

The epicentral area has a large number of other engineered structures like oil refinery plants, ground supported steel oil/fluid storage tanks, tall RC stacks/chimney stacks/TV towers, steel high-tension electrical transmission lines, steel communication towers, RC cooling towers, steel frame structures, and RC elevated water tanks on frame/shaft staging; these indicated only minor/no damage.

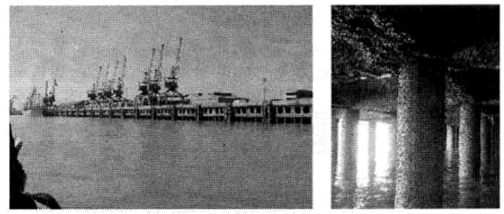

Figure 13: Six of the twelve jetties at the Wharf at Kandla port were damaged; flexural cracking of the piles at the jetty.

Figure 14: A 15° tilt in the 6-storey control tower at Kandla port due to liquefaction and consequent lateral spreading towards the bay.

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With several weeks gone by after the earthquake, it is now time to plan for rehabilitation of the persons rendered homeless by the earthquake. However, there is a severe shortage of trained structural engineers in the country with adequate expertise in earthquake engineering who can assess the damages and handle repair/seismic retrofit of the damaged buildings. In effect, the earthquake has also shown the urgent need to develop an earthquake engineering industry in India so that earthquake-related products and services can be made available to the affected communities on professional basis.

Initiatives, both short term and long term, are required to build capacity in the technical community to tide over this earthquake disaster as well as to develop preparedness for upcoming earthquakes in the country.

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