The Republic Day Earthquake
in the land of M. K. Gandhi, The Father of the Nation

Learning from Earthquakes :: A field report on structural and geotechnical damages sustained during the 26 January 2001 M7.9 Bhuj Earthquake in Western India

by
Sudhir K.. Jain
C. V. R. Murty
Umesh Dayal
Jaswant N. Arlekar
Sailender K. Chaubey

Department of Civil Engineering
Indian Institute of Technology Kanpur
Kanpur 208016, India

Statue of Mahatma Gandhi at Gandhidham,
Gandhi was born at Porbandar, 180km south of epicentral area

Contents...

EERI Reconnaissance Team for
the 26 January 2001 M7.9 Bhuj Earthquake in Western India

Learning from Earthquakes

EERI

Co-Team Leaders

Sudhir K. Jain
Department of Civil Engineering
Indian Institute of Technology Kanpur
Kanpur 208016
India

William R. Lettis
William Lettis & Associates
1777 Botelho Drive Suite 262
Walnut Creek, CA 94596
USA

Team Members

Donald Ballantyne
EQE International
1411 4th Ave Building Suite 500
Seattle, WA98101
USA

Umesh Dayal
Department of Civil Engineering
Indian Institute of Technology Kanpur
Kanpur 208016
India

Rakesh K. Goel
Cal Poly State University
Civil & Environmental Engineering
San Luis Obispo, CA 93407
USA

James Hengesh
URS Corporation
221 Main Street, Suite 600
San Francisco, CA 94105
USA

Praveen Malhotra
Factory Mutual Research Corporation
1151 Boston Providence
Turnpike P.O. Box 9108
USA

C. V. R. Murty
Department of Civil Engineering
Indian Institute of Technology Kanpur
Kanpur 208016
India

P. L. Narula
Formerly Deputy Director General
Geological Survey of India
Faridabad
India

Chandan K. Saikia
URS Corporation
566 El-Dorado Suite 100
Pasadena, CA 91101
USA

Mahendra Pal Singh

Krishna Vatsa

Virginia Polytechnic and State University
Engineering Science and Mechanics
305 Norris Hall
Blacksburg, VA 24061
USA

George Washington University
Department of Engineering
Management
707 22nd Street
Washington, DC 20052
USA

Jaswant N. Arlekar
Department of Civil Engineering
Indian Institute of Technology Kanpur
Kanpur 208016
India

Sailender K. Chaubey
Department of Civil Engineering
Indian Institute of Technology Kanpur
Kanpur 208016
India

Alok K. Goyal
Department of Civil Engineering
Indian Institute of Technology Bombay
Powaii
Bombay 400074
India

Introduction

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 quake caused a large loss of life and property. Over 18,600 persons are reported to be dead and over 167,000 injured; the number of deaths is expected to rise with more information coming in. The estimated economic loss due to this quake is placed at around Rs.22,000 Crores (~US$5 billions).

The earthquake was felt in most parts of the country and a large area sustained damages. 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 high as X on the MSK intensity scale. Several towns and large villages, like Bhuj, Anjaar, Vondh and Bhachau sustained widespread destruction. 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 multistorey RC frame buildings collapsed in Gandhidham and Bhuj in the Kutch region, and in the more distant towns of Morbi (~125km east of Bhuj), Rajkot (~150km southeast of Bhuj) and Ahmedabad (~300km east of Bhuj). At least one multistorey building at Surat (~375km southeast of Bhuj) collapsed killing a large number of people. The strong motion records obtained from the region at the Passport Office Building under construction in Ahmedabad city, indicate a peak ground acceleration of about 0.11g Source: http://www.rurkiu.ernet.in/acads/depts/earthquake/bhuj/index.html]. A preliminary report prepared by IIT Bombay is available at www.civil.iitb.ernet.in/BhujEarthquake/Earthquake_Web_Page.htm.

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 of the country in the recent times and the modern industrial constructions. Therefore, the performance of structures in this area will offer important lessons particularly from the points of view of efficacy of Indian codes and construction practices. While from an international standpoint, most of the damages now seen in the Kutch area may have already been known and documented after the past earthquakes across the world, 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.

The following provides a quick rundown of the salient structural and geotechnical damages recorded during a reconnaissance survey to capture important lessons from the aftermath of the quake conducted during 02-14 February 2001 by a EERI team of 16 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, seismologists, geophysicists, geotechnical engineers, structural engineers, and emergency managers. The investigation was supported by the Earthquake Engineering Research Institute (EERI), Department of Science and Technology, Government of India, New Delhi, and Indian Institute of Technology Kanpur.

A common site of destruction of the villages in the meizoseismal area.

Many surprises for common man: adjoining buildings with radically different performances!!

Common man learns: even RC frame buildings can break apart!!

Rubble of collapsed buildings being cleared at Anjaar. Narrow lanes caused significant casualties and made rescue and relief very difficult. Kudos to the rescue/relief workers for their daring efforts!!

Virtually nothing could be recovered from most RC frame buildings that collapsed. Clearing of debris from collapse of numerous multistorey RC frame buildings was an even bigger challenge.

A depressing scene of a village after the earthquake.

Relief distribution after the earthquake.

Temporary shelters in the town of Morbi.

Building Systems

Buildings in the affected area can be classified into two broad categories:

(a) The older non-engineered dwellings made with load bearing masonry walls supporting tiled roof or RC slab roof. The different types of masonry consisted of random rubble stone with mud mortar, random rubble stone with cement mortar, small block cut stone in mud/cement mortar, large block cut stone in mud mortar/cement, brick masonry in mud/cement mortar, and

(b) The newer reinforced concrete frame buildings with unreinforced masonry infills. The infills were of varied type, namely clay brick masonry in cement mortar, large block cut stone masonry in cement mortar, small block cut stone masonry in cement mortar, cement blocks in cement mortar, and hollow cement blocks in cement mortar.

In the former type, the damages are owing to ills of random rubble masonry that was extensively experienced in the aftermath of some of the recent Indian earthquakes. 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. 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 thik wooden logs as purlins and rafters, are among the notable deficiencies of such dwellings.

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 multi-storey buildings that collapsed, most had the ground storey left open for parking convenience with few or no filler walls between the columns. This created a top stiff inverted pendulum structure with insufficient strength and stiffness in the open ground storey, thereby rendering the same vulnerable. Most buildings with complete infills 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 infills 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.

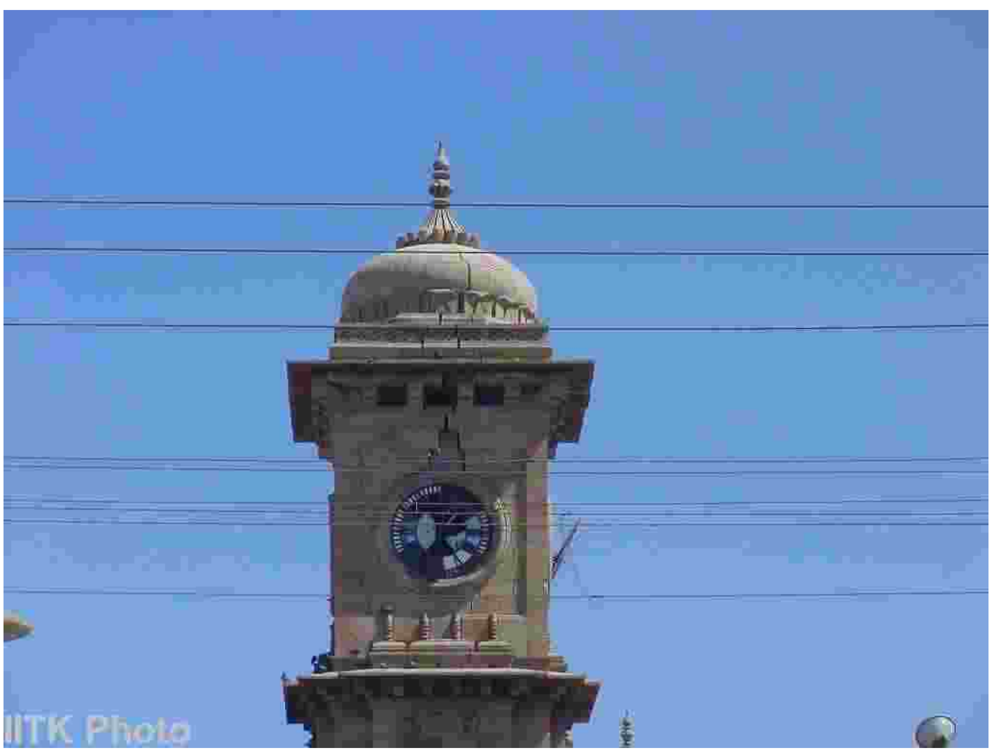
Monumental Structures

The area adjoining Kutch that includes districts of Rajkot and Jamnagar is termed as Saurashtra, which implies "one hundred nations". This region had a very large number of small kingdoms and hence, the affected area is rich in cultural and heritage structures. Numerous such structures sustained heavy damages during the earthquake. A major challenge is to resolve the conflict between being conservative in demolishing many such damaged buildings considering them unsafe and salvaging maximum possible heritage.

Damage to the Bhid gate at Bhuj. This gate seems to have been rehabilitated earlier also.

Partial collapse of the walls of the historic fort at Bhuj.

Collapse of the temple pagodas made of large block stone masonry at Halvad near Ahmedabad.



Clock tower at Morbi: vertical splitting of large block masonry.

Partially collapsed pagoda at the palace at Morbi.

Brick Masonry

Collapse of the upper storey of a building under construction at Bhachau village.

Collapse of the brick masonry railroad station building at Vondh.

Partial collapse of the roof and brick chimney at the Mangalore roof tile factory near Morbi. Close-up view shows the cyclic shear cracks in the upper portion of another precariously balanced brick chimney near Morbi.

Cement Block Masonry

A number of railway stations suffered extensive damages. Fortunately, at this location, no one was killed since at the time all the railway staff had gathered elsewhere for the Republic day flag hoisting ceremony.

Small Block Stone Masonry

Collapse of upper storey of a commercial building in old Bhuj.

Out-of-plane collapse of masonry wall.

Large Block Stone Masonry

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

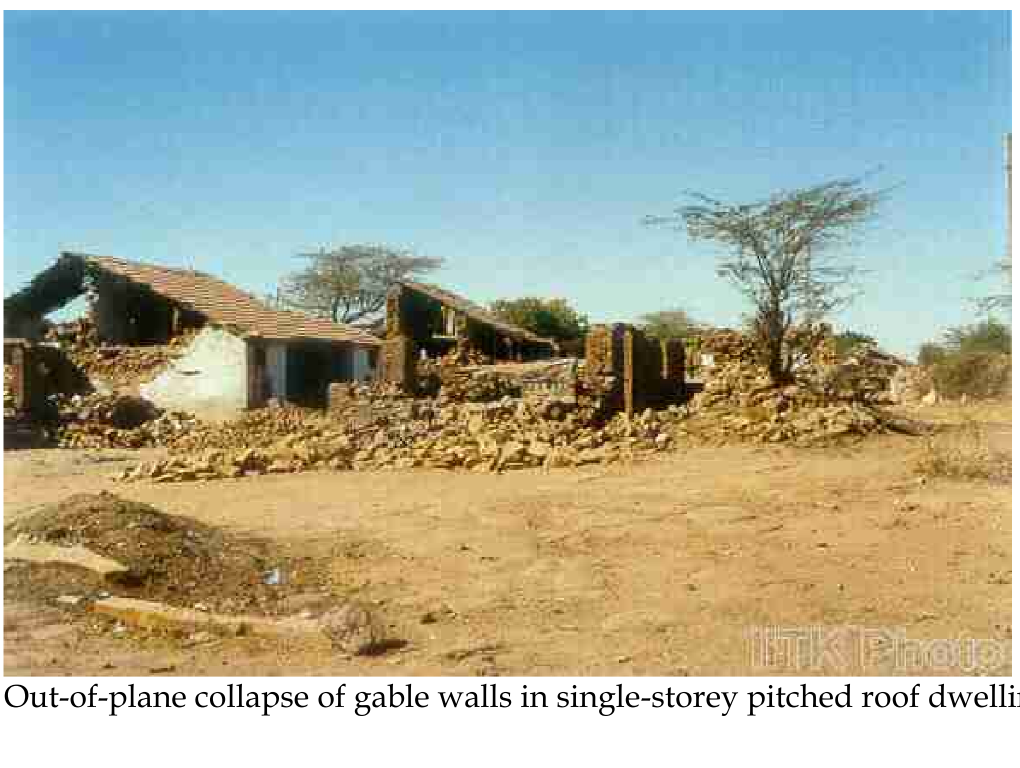
Collapse of the upper storey of the block masonry government office building at Bhuj.

Random Rubble Masonry

One two-storey random rubble stone masonry rail road signaling cabin with lintel band at Kandla port sustained minor damage, while another in the same area had a collapse of the upper storey.

Total collapse of traditional houses in random rubble stone masonry with mud mortar at Maliya and Samakhyali villages.

Collapse of random rubble stone masonry constructions along a street in Morbi town.



Out-of-plane collapse of gable walls in single-storey pitched roof dwellings.

Uneven out-of-plane collapse of the wythes of the stone masonry walls in single-storey building with RC slab roof near Ahmedabad.

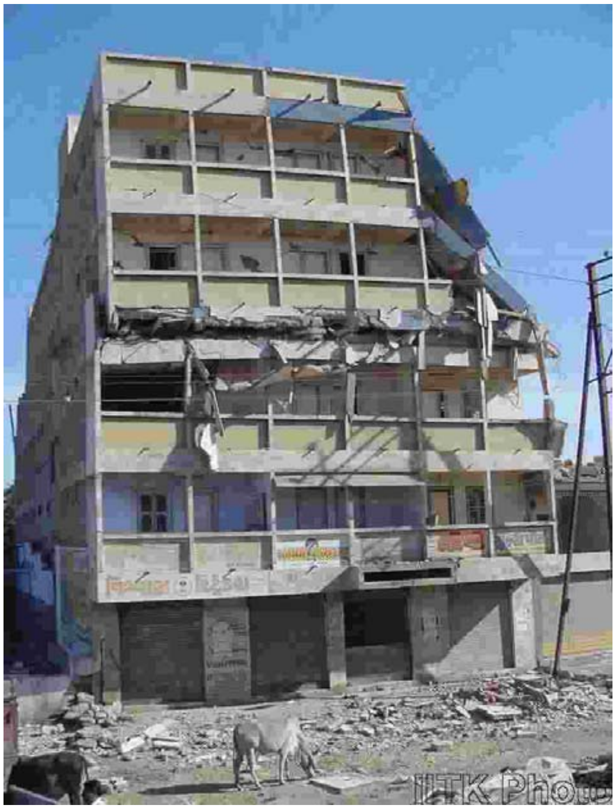
Reinforced Concrete Buildings

Total collapse of a portion of a 10-storey residential building in Ahmedabad.

Pancake collapse of 4-storey L-shaped RC framed school building in Ahmedabad.

Collapse of open ground storey RC frame residential building in Bhuj.

Numerous cases of dislodging of the weakly connected overhead storage water tanks were observed in the entire earthquake affected area. Picture shows dislodging of water tank appendages from atop unfinished and finished RC frame buildings in Bhuj.



Collapse of intermediate storey in a 6-storey RC frame commercial building at Bhuj.

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

Most RC buildings with open ground storeys that collapsed showed a very common practice of poor detailing; 6mm diameter lateral ties in the columns with 90º hooks and longitudinal spacing as large as 30cm. This did not provide the required confinement to the core concrete.

Collapse of a portion of 6-storey residential building at Anjaar; the portion that collapsed had an open ground storey.

Collapse of one-half of the 14-storey RC frame residential apartment building in Ahmedabad; the collapsed portion had a swimming pool on the roof, unlike the other half that is standing.

At Gandhidham, the right building had ground storey collapse. The two buildings shared a common wall.

Collapse of upper storey of buildings at Gandhidham. It is suspected that this may have been caused by inadequate lap lengths in the column reinforcement.

Collapse of ground storey of a two-storey RC frame building in Manfara village.

Collapse of the RC frame shelter at a bus stop near Pundi village.

One of the numerous RC frame multistory buildings at Ahmedabad that withstood the earthquake shaking with only minor cracking in the masonry infill walls.

The practice of floating columns in the upper storeys is very common in the cities in India. Close-up view shows shear cracks in the cantilever stub beam supporting a floating column in a 4-storey RC frame residential building in Ahmedabad.

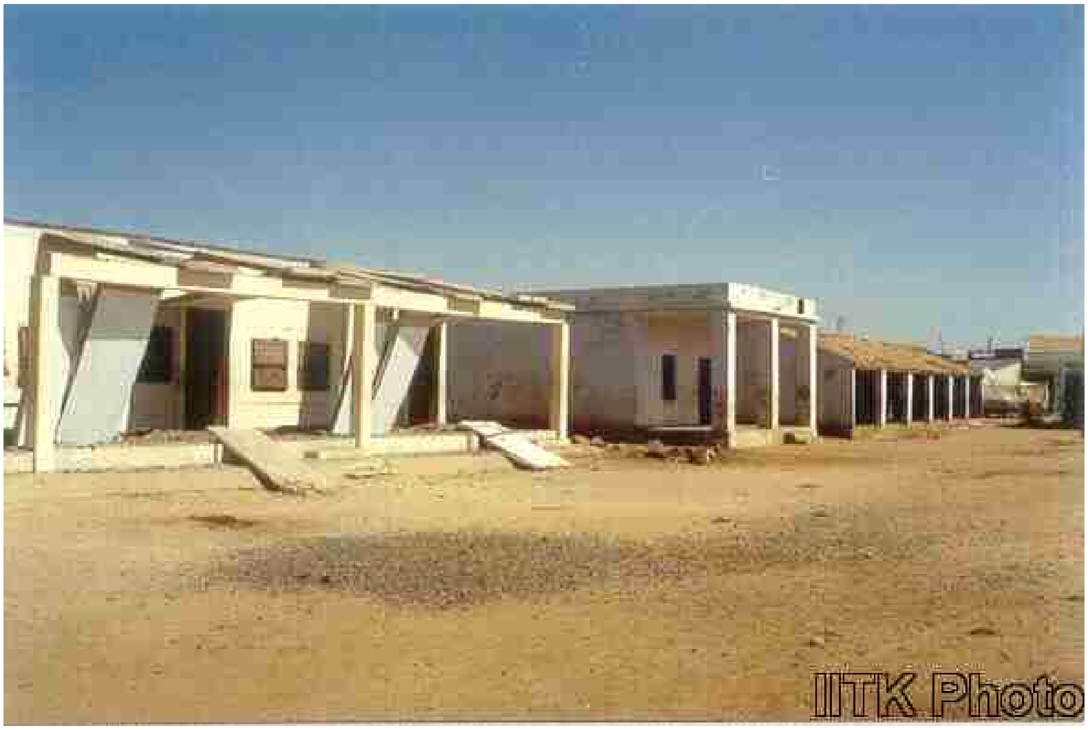
These columns left for future extension show inadequate spacing of stirrups.

The area also offered examples of good RC detailing; residential building of Telecom department under construction at Bhuj.

Severe shear cracking sustained by the RC elevator core wall in a four-storey RC frame building in Ahmedabad.

Insufficient connection between the RC elevator core and rest of the building lead to the underutilization of the lateral strength and stiffness of the elevator core.

Precast Constructions



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.

Partial collapse of the roof due to failure of ties between prestressed concrete trusses of the warehouse at Kandla port. Close-up view shows the failure of the connection welding between the tie and the truss.

Retrofit of RC Buildings in a Frenzy

Buildings with open ground storeys in the affected area were "propped" by structural steel sections and wooded posts as an immediate measure by the residents.

Improper jacketing of columns that was practiced immediately after the earthquake in numerous buildings at Ahmedabad. The new frame to be encased in concrete rested on the finished ground floor and not carried to the foundation. Similarly, it did not connect well with the beams above. Even the plaster of beams and columns was not removed.

In some instances, a structural steel member was placed adjoining the RC damaged column. The old columns together with the adjoining steel member were jacketed with concrete. In this instance, the steel column was taken below the floor level but not extended till the foundation.

Bridges

The only road link between the Kutch and Saurashtra areas is the road bridge at Surajbadi, which was damaged; this stalled traffic for a few days before it was temporarily restored for slow traffic conditions. Damages to other major road and rail bridges are also recorded.

The old multispan balanced cantilever RC slab bridge with suspended spans at Surajbadi sustained severe damage at the bearings at most piers, and has lateral movement of the deck at one of the piers.

Close-up view of the damage sustained at the bearings on most piers of the old Surajbadi bridge.

Prestressed concrete girder bridge nearing completion at Surajbadi. Completed spans sustained substantial damage like pounding of the deck slab, horizontal movement of girder, and damage at the bottom of girders.

The longitudinal movement of the new Surajbadi bridge superstructures led to pounding at the deck slab level.

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.

The movement of the girders in the new Surajbadi Bridge along the longitudinal and transverse directions imposed severe strains on the neoprene bearings and spalling of cover concrete at the bottom of the girders. More details on this bridge are also available at www.tcpl.com

Lateral movement of soil at the abutment of the four-span RC bridge near Vondh.

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

This pier at the RC bridge near Vondh was found to have a tilt. Considerable liquefaction was observed at the site.

Damage to pipe culvert. The site had considerable liquefaction.

A number of RC slab culverts on stone masonry abutments sustained damage.

Lateral movement of the wing wall at the abutment of RC slab bridge.

A number of old masonry arch bridges for Indian railways sustained extensive damage. This bridge is about 88 years old.

Unsymmetrical failure of stone masonry arch railway bridge.

Geotechnical Damages

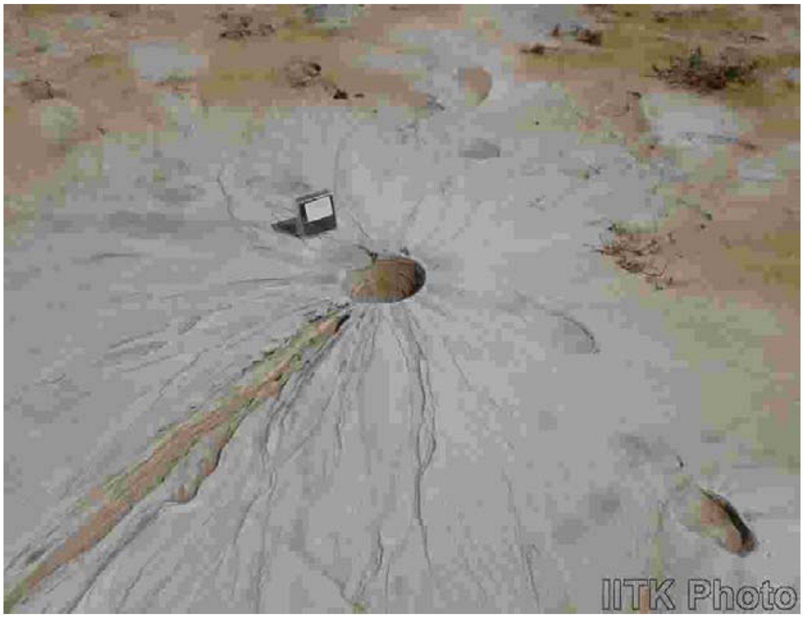
The earthquake caused excellent examples of large-scale liquefaction and embankment failures. The Great Runn of Kutch, the Arabian Sea and the Little Runn of Kutch lock the affected area on its three sides. This enclosed area at near sea level sustained extensive liquefaction (a phenomenon of *quicksand* condition by virtue of which the soil looses the capacity to hold structures in place). Five earth dams failed during the earthquake. The earthen embankments of the railroad and highways also suffered widespread damage.

Liquefaction Effects

Extensive liquefaction in the Runn of Kutch; this did not affect the performance of the high-tension transmission lines in the area.

Extensive liquefaction near a 3-storey RC frame office building at Kandla port; building sustained only minor cracks in the walls, but settled down by about 70mm.

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



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

Extensive lateral spreading of the ground due to liquefaction at Amarsar near the Great Runn of Kutch.

Earth Dams

Cracks along the crest of the Tappar Dam

Collapse of the random rubble masonry intake tower at the Tappar Dam.

Longitudinal cracks along the crest and the downstream slope of the Kaswati Dam.

Lateral spreading at the toe of the Kaswati Dam.

Failure of the upstream slope of the Fatehgadh dam.

Failure of the upstream crest of the Fatehgadh dam.

Massive cracks in the upstream embankment near the toe of the Fatehgadh dam.

Lateral spreading of the downstream section of an earthen dam at Rudramata.

Cracks along the crest and vertical settlement of the Suvi dam.

Failure of sea wall at Navlakhi port; over 50 meters stretch of the wall was washed away into the sea.

Railroad and Highway Embankments

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.

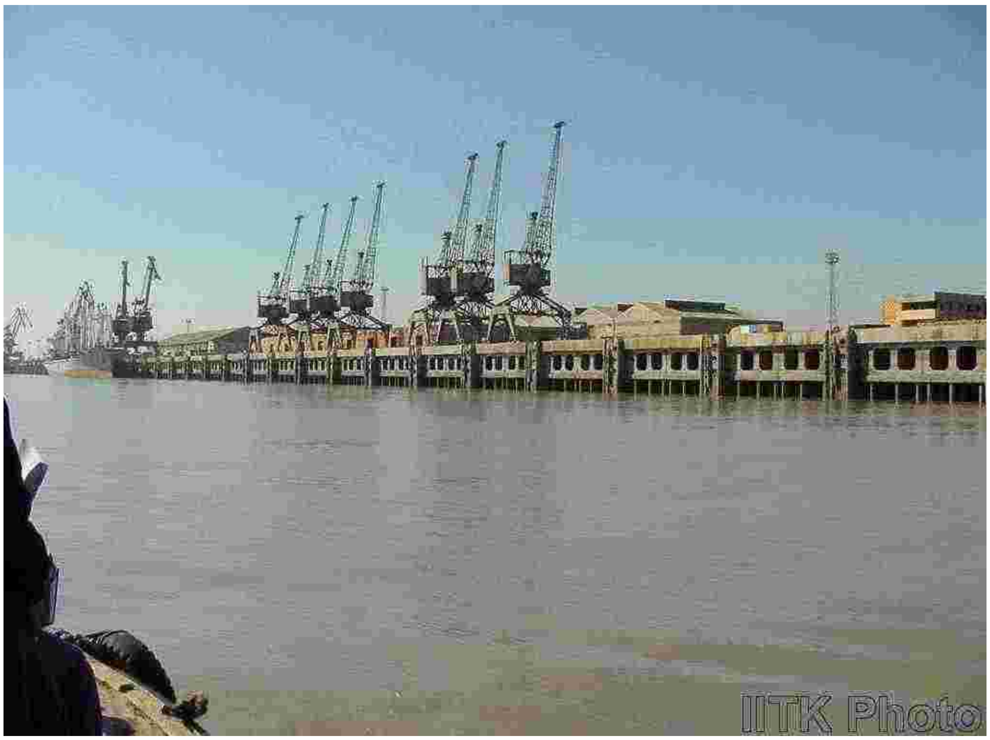
This rail embankment at Vaka Nala of about 5 meters height suffered extensive damage. The rails were hanging by about 1.0 to 1.5 meters after the earthquake. Ground liquefaction was observed at the base of the embankment.

Damage to highway pavement near Rapar due to lateral spreading of soil.

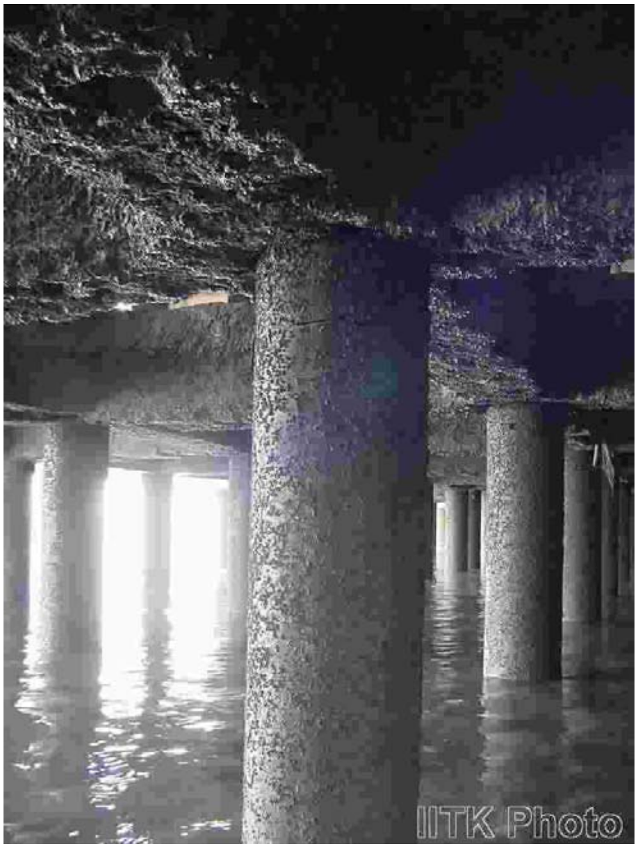
Damage to kerb of highway pavement due to lateral spreading of soil.

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. However, the oil refinery plants, oil tanks, tall TV towers, high-tension electrical transmission lines, steel communication towers, and elevated water tanks suffered only minor damage.



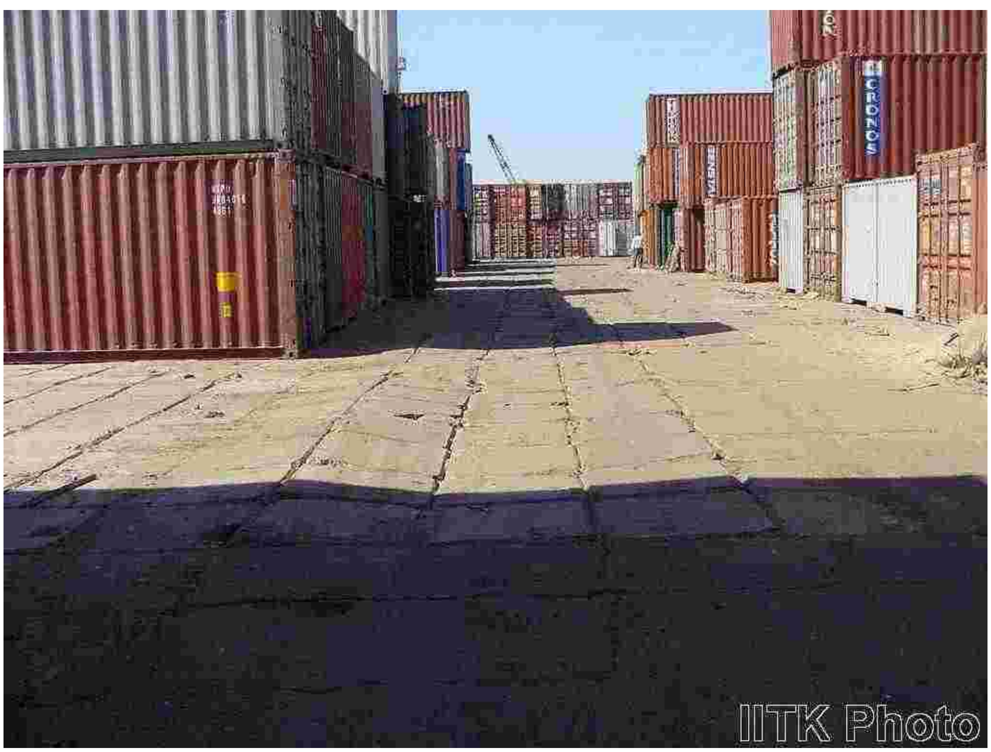
Wharf at Kandla port. Next picture shows damage to the pilons.



Flexural cracking of the piles at the jetty at Kandla port.

Flexural and shear cracks at the beam-column joint at the knee-bent frame supporting craft jetty at Kandla port.

Severe damage (cyclic shear cracks) to the exterior short columns at the ventilators of the warehouse at Kandla port; opening of ties and buckling of longitudinal steel.



Undulations of floor tiles of the container terminal at Kandla port due to extensive liquefaction.

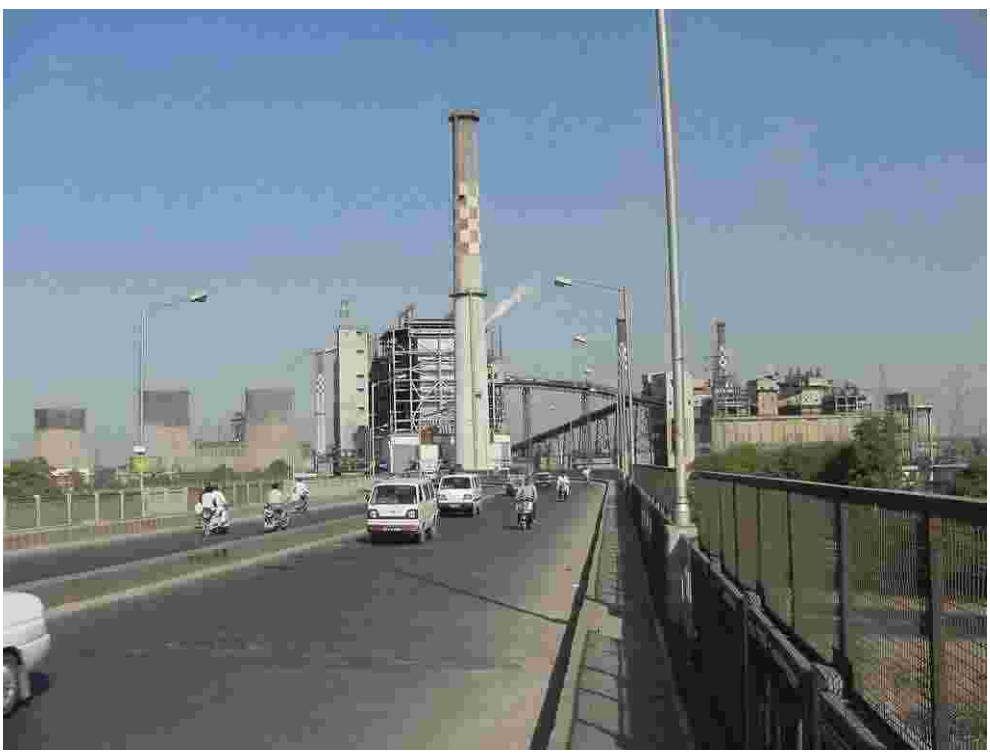
A 15^{o} tilt in the 6-storey control tower at Kandla port due to liquefaction and consequent lateral spreading towards the bay.

Good Performances

The earthquake did not cause significant damage to elevated water tanks on framed staging, steel communication towers, steel HT line towers, steel oil storage tanks, RC stacks and RC chimney stacks.

Steel oil storage tanks at Kandla port and elsewhere did well during the earthquake.

Steel HT lines near Khawda and elsewhere did well during the earthquake.



RC chimneystacks, RC cooling towers and steel frame structures at the thermal power plant in Ahmedabad performed well during the earthquake.

150 meter high TV transmission tower in Ahmedabad did not sustain any damage during the earthquake, even though the adjoining studio facility sustained significant damage in infill walls.

A Technological Crisis...

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 region who can assess the damages and suggest measures for 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 on 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. In the short run, in the following steps are urgently required:

(a) Sensitise the civic administrators of the major towns/cities of the gravity of the situation and provide them with critical inputs to develop a robust rehabilitation program, which includes the damage assessment of the building stock, and their repair/retrofit/reconstruction.

(b) Training to engineers in Ahmedabad, Gandhidham, Jamnagar, Morbi, Surendranagar and Rajkot on how to assess damages sustained by the buildings in the affected area.

(c) Insights into the performance of structures to the architects/engineers in the affected area, and the steps required to take-up retrofit of the large stock of buildings distressed by the quake; and

(d) Train the builders to do the relatively new activity for them, namely repair/retrofit/reconstruction.

In the long run, the following bold steps are required:

(a) Develop legal and technical framework to ensure that all new constructions fulfill seismic requirements.

(b) Evolve an implementable seismic retrofit policy for handling a huge building stock in the country that may be seismically deficient.

(c) Include earthquake design and construction in the curriculum in the Indian technical universities/institutes, and

(d) Conduct vigorous and practical short-term courses for training practicing engineers and architects on seismic design of reinforced concrete buildings and bridges.

Unfortunately, in a large country like India, too few individuals and institutions are engaged in earthquake engineering. A major focus has to be placed on institutional and manpower development in this critical area. The National Information Center of Earthquake Engineering (NICEE) and IIT Kanpur would like to contribute to the above cause, in all possible ways to meet the above long term and short term demands.

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Note: The pedestal alone is shattered,
the *Father of the Nation* is still standing.

This is a special presentation of
National Information Center of Earthquake Engineering (NICEE) at IIT Kanpur,

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