THE KUTCH EARTHQUAKE OF JANUARY 26, 2001

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1 INTRODUCTION

Kutch (Kutch) region in Gujarat State of India was severely shaken by a powerful earthquake at 8:46 am on 26 January 2001 of the India Standard Time, which 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 20,000 persons are reported to be dead and over 167,000 injured. The estimated economic loss due to this quake is placed at around US$5 billions. The entire Kutch region of Gujarat sustained highest damage with maximum intensity of shaking as high as X on the MSK intensity scale.

Seismological data indicates that a severe earthquake measuring Ms 7.7 (NEIC) Mw 7.7 (NEIC) Mw 7.6 (HRV) occurred at 03:16 UTC (8:46 a.m. local time) in the southwestern province of Gujarat, near the Gulf of Kutch. The hypocenter was placed at a shallow depth of about 17 km below the surface and both the NEIC and HRV fault plane solutions indicated predominantly reverse faulting along a moderately dipping, nearly east-west trending fault plane with a slight sinistral sense. This earthquake has caused diluted surface fault ruptures.

The investigation by the earthquake engineering sub-committee of The Japan Society of Civil Engineers (JSCE) has been undertaken between March 16 and 24, 2001. The investigation on the 2001 West India earthquake covered various aspects of the earthquake. This article presents an overview of the investigation results of the JSCE Kutch earthquake investigation team. The article covers the geology, tectonics and seismicity of the earthquake region, seismic intensity and the characteristics of strong motion records and damage to civil engineering structures. The findings and observations of the investigation aforementioned aspects of the earthquake are briefly presented and discussed herein.

2 GEOGRAPHY AND GEOMORPHOLOGY

Kutch or Katchchh region has a population of 1,252,507 according to 1991 census in Gujarat State of West India, bounded on the North by Pakistan. It is largely barren except for a fertile band along the Gulf of Kutch in the Arabian Sea. Mandvi, Bhuj, and Kandla, a new port, are the main cities and towns. It is the largest district of the state of Gujarat and the second largest district in India covering an area of 45,612Sq Kms. The Great Rann of Kutch dominates a major portion of the region. The Great Rann of Kutch and the Little Rann of Kutch are uninhabitable deserts, which during the monsoon season (June to October) is often completely submerged by floods (Figure 1).

Geomorphologically, Kutch (Kutch) is categorized into four major E-W trending zones (Figure 2):

1.Coastal Zone - demarcating the southern fringe

2.Kutch Mainland - divided into the central portion comprising rocky upland, northern hill range and coastal plains,

3) Banni Plains (less than 5m MSL)-marked by raised fluviomarine sediments, mud flats and salt pans and

4) The two Ranns Great Rann (~ 2m MSL) in the north and Little Rann in the east comprising vast saline wasteland. The boundaries of these main geomorphic zones are bounded by the major E-W trending faults.

The Kutch landscape comprises an array of tectonogenic geomorphic elements in the form of uplifts and residual depressions. Elevated landforms are occupied by Mesozoic and Tertiary rocks, whereas the residual depressions or low-lying regions between the uplifts consist of Quaternary sediment successions marked alluvial river terraces in the rocky mainland and the mud-flats and salt pans in the Great and Little Ranns and Banni Plains. The general forms of the uplifts are marked by domes and asymmetric anticlines. All major uplifts are bounded, at least on one side, by a fault or a sharp monoclinal flexure, and on the other side by gently dipping peripheral plains, the strata (Tertiary) in which dip gently into the surrounding residual depression (Biswas, 1987).

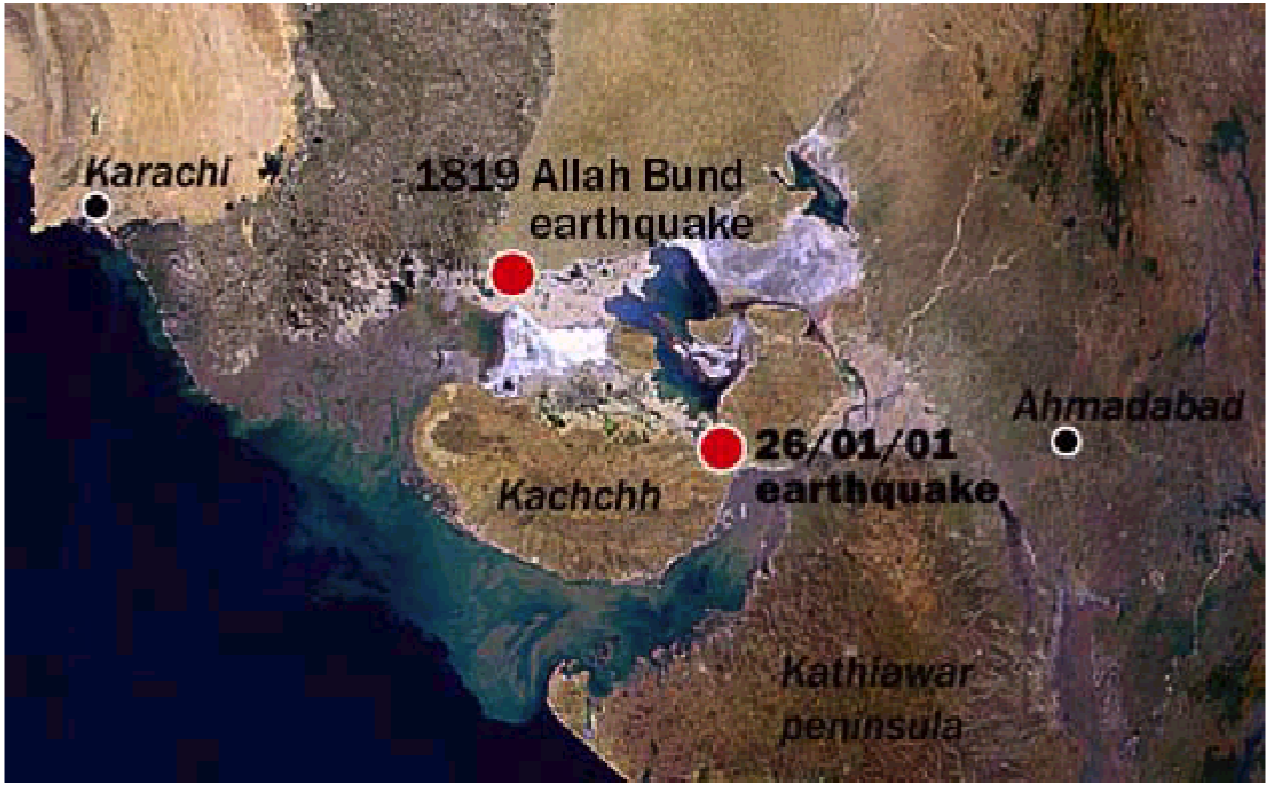


Figure 1 A satellite view of the Kutch (Kachhh) region and earthquake epicenter

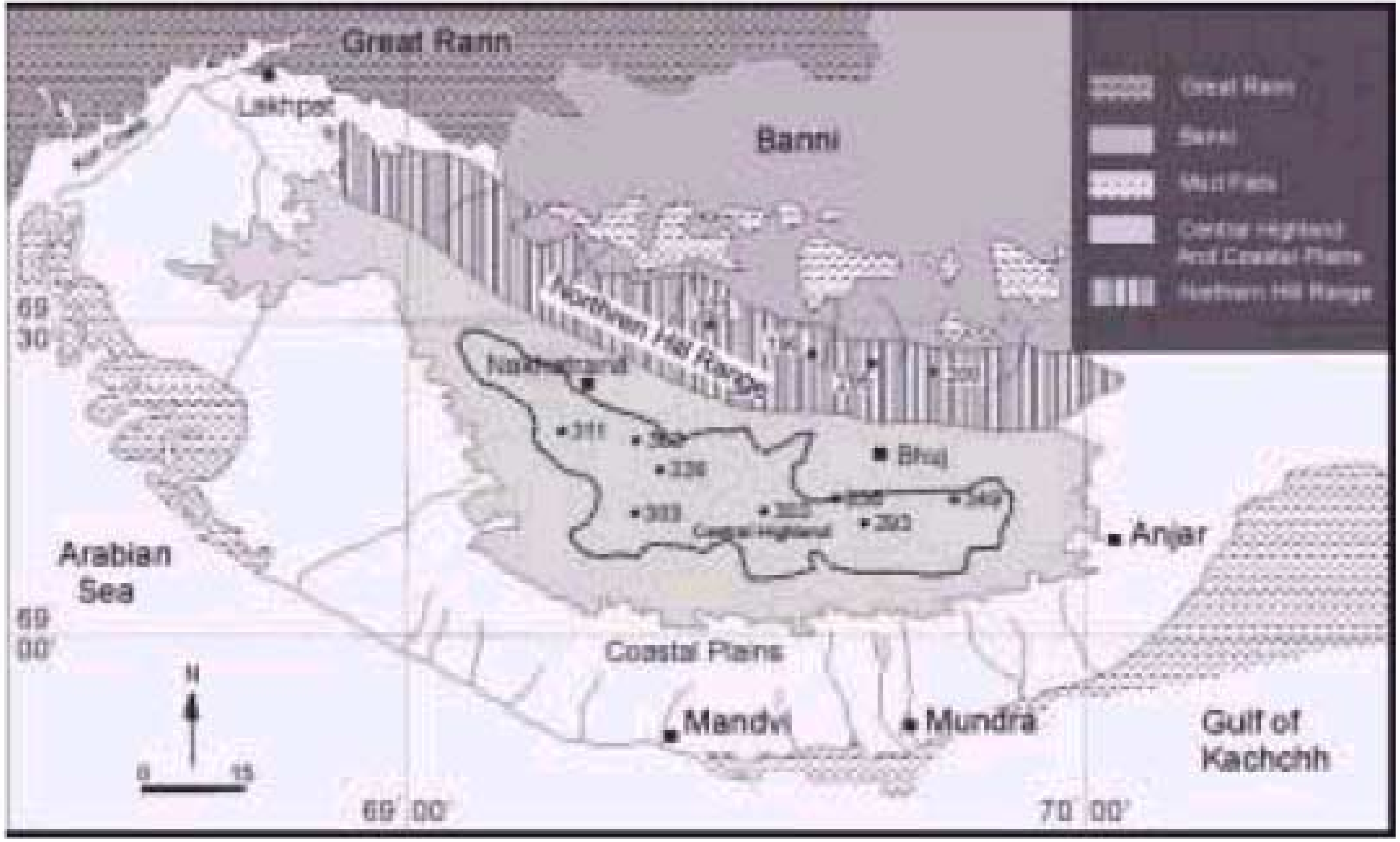


Figure 2 Geomorphological Map of Kutch (Kutch)

3 GEOLOGY OF KUTCH AND AHMEDABAD BLOCK

Sedimentary rocks ranging in age from Jurassic to Eocene age cover Kutch region (Figure 3). These sediments have a zone of Deccan trap volcanics sandwiched between Jurassic rocks of the northern part and Eocene sedimentaries in the south towards the coast. Limestones, shales and sandstones are the most common rocks. The Jurassic rocks have an estimated thickness of 1950 m and crop out in three anticlinal ridges trending E-W. Owing to an E-W fault the whole sequence is repeated. The northern range is about 160 km long and broken in to four islands (Pachham, Karir, Bela and Chorar) in the Ran of Kutch. The middle ridge is 190 km long trending ESE from Lakhpat on the west. The

southern ridge, south of Bhuj, is 65 km long and forms the Charwar and Katrol hills. The Jurassic rocks are repeated in these two ridges. The main outcrop, of which they form parts, is cut by an E-W strike fault.

An isolated but large outcrop, on which Wagur and Kantkote stand, is about 80 km long, in NE Kutch. These anticlines show transverse undulations so that the domes like parts have been separated from each other by denudation. Both Eocene and Jurassic rocks are fossiliferous. The Eocene rocks are exposed along the southern fringe of the Kutch peninsula as a thin band bounded by Deccan traps on the north.

Recent marine deposits on which Jurassic rocks form outcrops cover the northern part of the Kutch peninsula. The coastal areas have thick alluvial and marine sediments of recent origin. This area seems to be undergoing some marine recession. A major paleo-rift valley lies along the east west direction passing through the Kutch region.

Sedimentary rocks of this region are generally well indurated and behave like hard rocks. The pore spaces are mostly cemented with calcium carbonate and therefore are mostly impervious. The Deccan Traps are exposed along the southern part of the Kutch peninsula.

Mesozoic rocks of Kutch region are exposed in three chains of east-west trending ridges. The 2000 m thick succession of marine sedimentary rocks represent a phase of transgression of sea along the west coast during Jurassic-Early Cretaceous times. The succession has been intruded by various sills and dikes and overlain by Deccan Traps of same age.

The RC buildings in Ahmedabad city, which is about 210 km far away from the epicenter, suffered damages of different degree and the maximum ground acceleration was 0.11g. Therefore, the geology of the basin in the vicinity of the Ahmedabad City is briefly outlined according to a recent publication by Banarjee et al. (2000). The Cambay basin trending almost NS, in which Ahmedabad city is located is a rift sag Tertiary basin, in the western onshore part of India includes Mehsana, Ahmedabad,

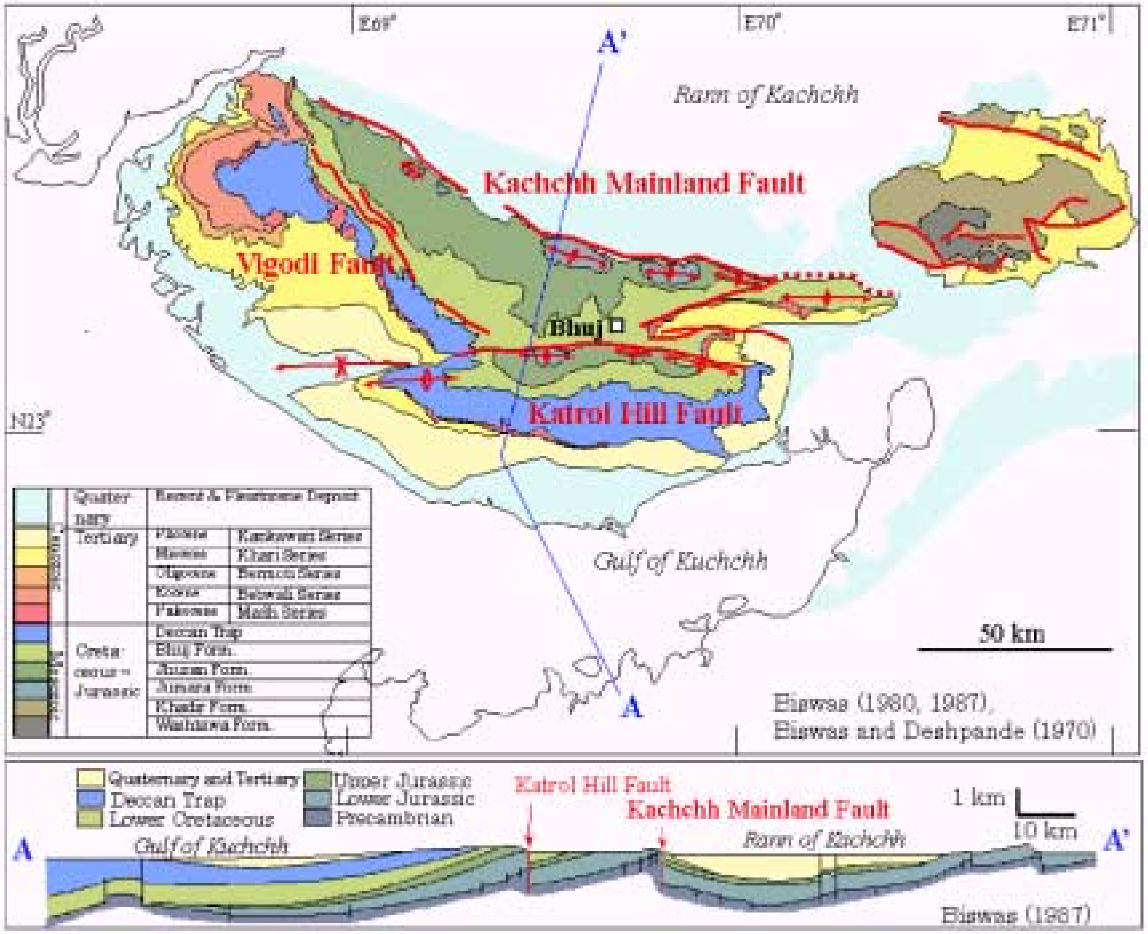


Figure 3 Geology of Kutch (Katchchh) region (after Biswas 1987)

Tarapur, Broach, and Narmada blocks, separated by faults aligned transverse to the general north–south axis of the rift. The area consists of Deccan trap, Cretaceous and Pre-Cambrian rocks. Deccan trap rocks are mainly extrusive rocks. Cretaceous rocks consist of shale, sandstone, coal, siltstone, limestone and conglomerate. Figure 4 shows a geological cross section along the east-west direction of the Cambay basin nearby Ahmedabad City. At the top Neogenic sediments consisting of sand, silt, clay and alluvium layers exist and its maximum thickness is about 2250m at the center of the basin and its thickness diminishes towards the east and west boundary faults of the basin.

4 SEISMO-TECTONICS OF KUTCH REGION

Tectonically, the Kutch is situated in the area where northwestern margin of the Indian continental shield meets the geosynclinal belt of the Sindh-Baluchistan. Thus, this marginal portion of the Indian shield forms a mobile zone characterized by block faulting and consequent folding. Block faults are typical of a basement made up of old rocks already consolidated by Pre-Cambrian orogenic movements. This marginal mobile belt of the Indian shield extends along the shelf zone with its coastal counterpart of the West Coast from Bombay to Kutch through Surat and Broach coasts and Saurashtra peninsula, reaching its maximum intensity near Kutch where it borders the geosyncline of Sindh-Baluchistan.

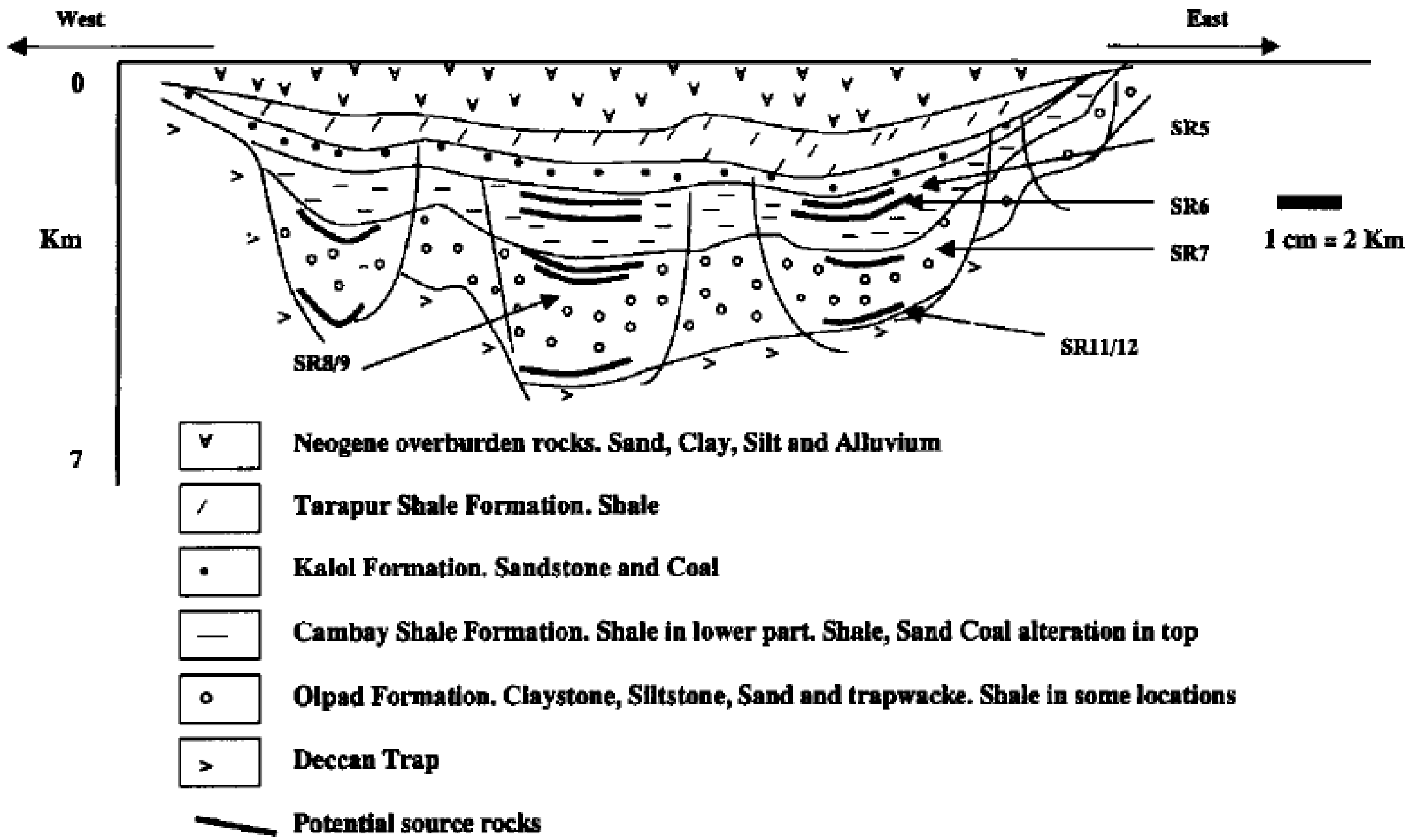


Figure 4 Geologic cross-section of Cambay Basin near Ahmedabad

Regionally, the structure of the Kutch is characterised by a series of uplifts along master faults (upthrusts) and along the Delhi tectonic trend that were reactivated during geologic time. Narrow linear zones of folding mark the faulted margins of the uplifts; a string of asymmetric domes and brachy anticlines occurs along these tectonised zones. Igneous intrusions such as laccoliths, plugs, sills and dyke swarms are localized in these zones. The Mesozoic strata are folded, faulted and intruded by igneous rocks. The Tertiary strata which warp around the Mesozoic highs in contrast, show very gentle dips and lie over the eroded Mesozoic folds in some places, bearing testimony of a major pre-Tertiary tectonic movement.

The Kutch Mainland is bounded by following major regional faults, which are responsible for its existing configuration. These bounding faults are (1) Kutch Mainland Fault striking ESE -WNW to E-W forming the northern limit of the Mainland. This fault has also caused southward tilting of the Mainland and thereby has greatly influenced the deposition of Mesozoic and Tertiary sequences, (2) Offshore West Coast Fault striking NW-SE and marking the western limit. It is probably the extension of the fault which is believed to have caused the almost straight west coastline of India, and (3) Gulf of Kutch Fault and the Little Rann of Kutch Fault System bounding the southern and eastern limits of the Kutch Mainland respectively (Biswas, 1987).

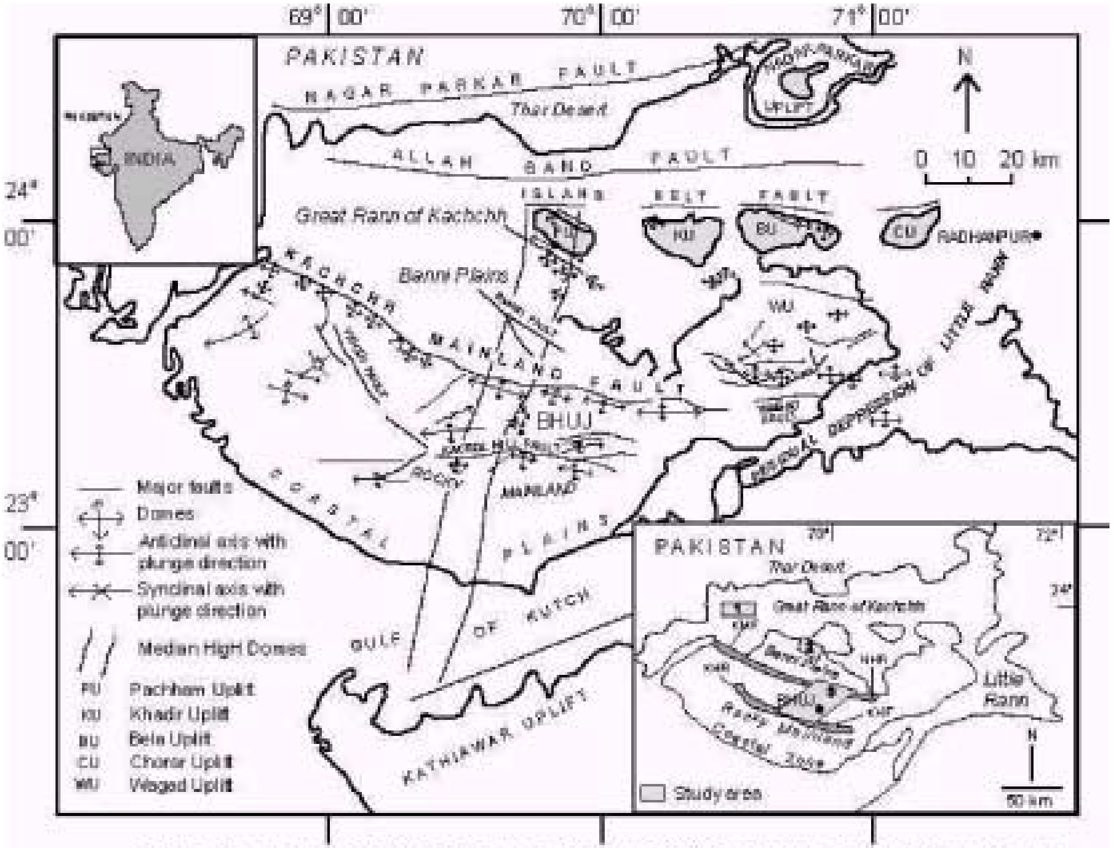
The main structural elements recorded by various workers (Biswas 1987), which played significant role in the post-Mesozoic geological and geomorphological evolution of Kutch Mainland are;1. Katrol Hill Fault 2. Vigodi Fault, 3. Little Rann of Kutch Fault system, 4. Naira River Fault, 5. Bhujpur Fault,

6. Vinjhan Fault, Vinjhan Anticlinal Nose and Kothara Embayment, 7. Gulf of Kutch Embayment, 8. Narayan Sarovar Anticlinal Nose, 9. Bhachau Anticlinal Nose (Figure 5).

Paleoseismicity record and several seismic events point to a continued tectonic activity. As a result the Kutch has experienced several episodes of earth movements due to successive tectonic upheavals along these lineaments all throughout the Cenozoic. Numerous oblique cutting subordinate faults developed during various tectonic events trending N-S, NNE-SSW, ENE-WSW and WNW-ESE.

The seismicity of the Kutch region is associated with the interaction of Indian plate with Euroasian plate. Although the indentation of the Indian plate into the Euroasian plate is mostly accommodated by the sinistral Chaman fault, it seems that thrust type faulting and associated folding of the sedimentary rocks are also taking place along this plate boundary zone. Figure 5 & 6 illustrate possible active faults in the region of Kutch (Malik et al. 2000). These faults are as follows; a) Nagar Parkar Fault, b) Allahbund Fault, c) Kutch Mainland Fault, d) Katrol Hill Fault, e) Naira River Fault, f) Bhujpur Fault and g) Wagad Fault.

The region that continues to be tectonically an active area and it is designated to seismically active zone V of the Indian Sub-continent. Although, the seismic risk of Kutch region is comparatively less than the Himalayan and the other active areas, Kutch region has produced during very recent times



Structural framework of Kachchh (after Biswas and Deshpande, 1970). Inset show generalized geomorphic zones of Kachchh. Shaded boxes in the lower inset shows area of study [1] and [2] detailed trench studies in Great Rann-Banni Plain, [3] study area in rocky mainland. NHR - Northern Hill Range, KHR - Katrol Hill Range, KMF - Kachchh Mainland Fault and KHF - Katrol Hill Fault.

Figure 5 Structural Geological Map of Kutch region (after Malik et al. 2000)

Figure 6 Spatio-Temporal distribution of earthquakes in Kutch region (Malik et al, 2000)

one of the greatest known earthquakes, viz. the 1819 Allahbund earthquake rated. The seismic aspects of the region are mostly based on palaeo-seismological studies. Therefore, it is important to evaluate the spatio-temporal event distribution in the region. Figure 6 shows the spatio-temporal distribution of earthquakes in Kutch region together with well-known faults in the region mentioned previously. Most of epicenters of earthquakes are closely associated with well-known faults. Large earthquakes are mostly associated with Allahbund fault while some large earthquakes seem to be associated with Kathiawar uplift.

5 SEISMIC CHARACTERISTICS OF THE EARTHQUAKE AND FAULTING

5.1 Earthquake Mechanism

Kutch (Kutch) earthquake occurred at 8:46 AM on India Standard Time on 26 January 2001. Various seismological institutes obtained the faulting mechanism of the earthquake and its magnitude. Table 1 gives the seismic characteristics of the earthquake and the focal plane solutions are shown in Figure 7. Almost all of the focal plane solutions obtained by various institutes implied that the earthquake was caused by thrust faulting with a slight sinistral sense and fault planes must have N60-80E strikes. The plane dipping to south should be steeper than the plane dipping to North. The solutions obtained by Yagi-Kikuchi and Kikuchi-Yamanaka indicated the surface displacement should be small even though the displacement is more than 5m at the hypocenter. The epicenter determined by the India Meteorological Department (IMD) is somewhat different from those of USGS and HARVARD. The field observations and aftershock distributions supports the locations of the epicenters obtained by USGS & Harvard . Indian Geological Survey (IGS) released 250 aftershock data until the end of February 2001. By assuming that the fault was planar, the following equation of the plane was determined by using the least square technique for a region bounded by 69.5-71.0E & 22.5-24.0N:

$$f = 936 - 26.52LON + 38.69LAT$$

The unit of f is in kms. From this function, the fault plane has been inferred to be dipping SW with an inclination of 47° and its strike is N53E. This fault plane is quite similar to those found by HARVARD and USGS focal mechanism solutions. Figure 8 shows a three-dimensional perspective view of the determined fault plane with the epicenters and hypocenters of the aftershocks. Although this earthquake did not produce a remarkable fault scarp, the surface trace of the plane should appear along an alignment extending from Khadir Island, passing the north of Chobari and Lodai in Banni plains and it should terminate somewhere the 30km north of Bhuj. This estimation is quite consistent with the surface ruptures, cracks and deformation zones observed in the earthquake area.

5.2 Faulting

As stated previously, there was not any well-defined fault scarp on the ground surface. It seems that many earthquakes in Indian plate do not result in well-defined fault scarps. This was claimed to be due to the low stiffness of the earth's crust of the Indian plate. Nevertheless, some fault scarps could be observed along the roadcuts during site investigations. Figure 9 shows a fault scarp near the northern

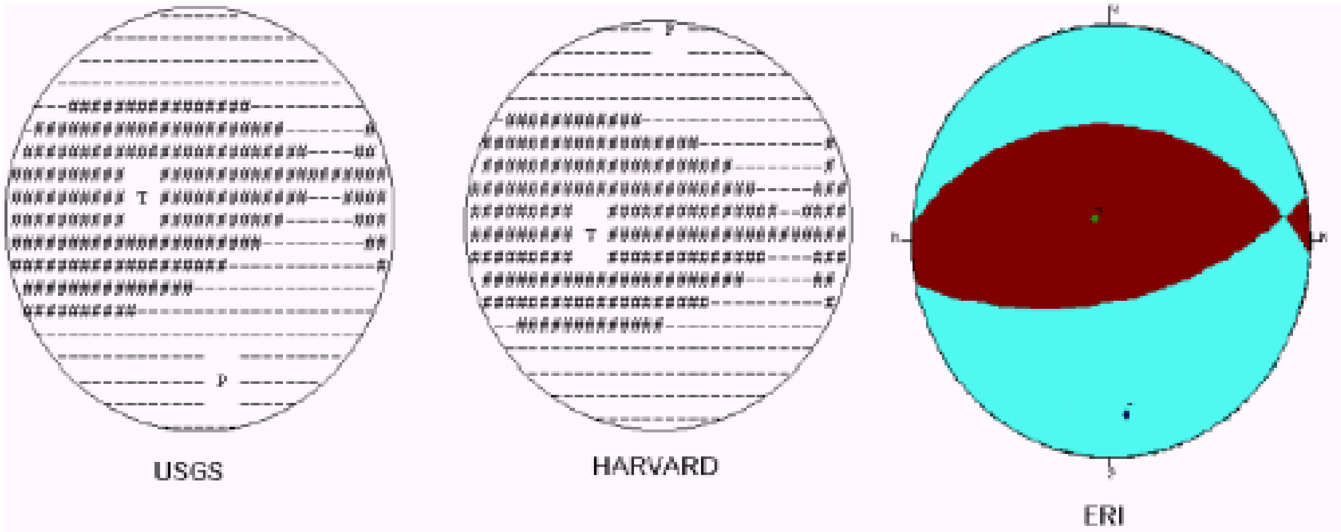


Figure 7 Fault plane solutions of the Kutch earthquake computed by various institutes

Table 1 Seismic parameters of the Kutch earthquake computed by various institutes

Institute	M_L	M_s	M_w	LAT (N)	LON (E)	H km	Plane 1			Plane 2			Dmax (cm)
							Strike	Dip	Rake	Strike	Dip	Rake	
HARVARD			7.6	23.45	70.34	18	65	50	50	297	54	127	
USGS		7.9	7.5	23.40	70.32	17	60	66	62	292	36	136	
ERI		7.9	7.6			18	78	58	51	276	33	105	540
IMD	6.9			23.60	68.60								

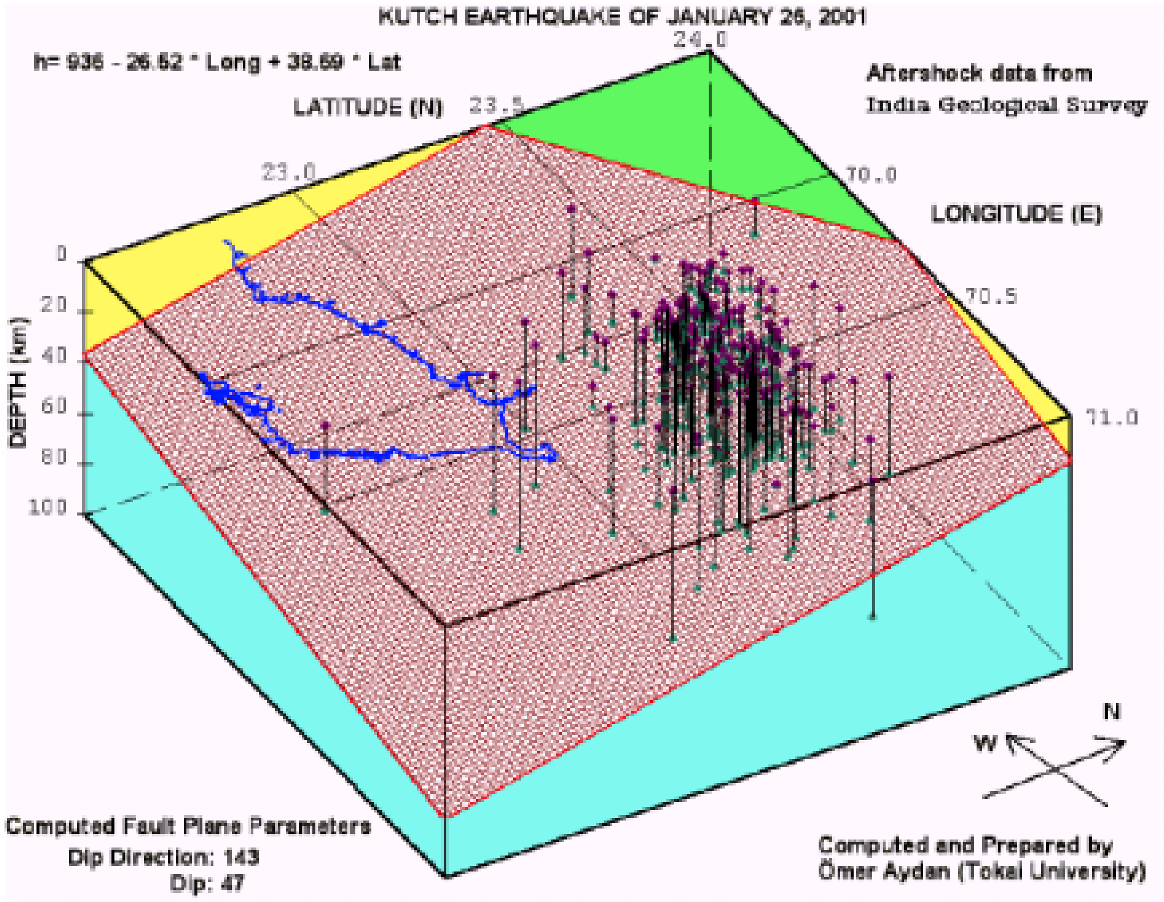
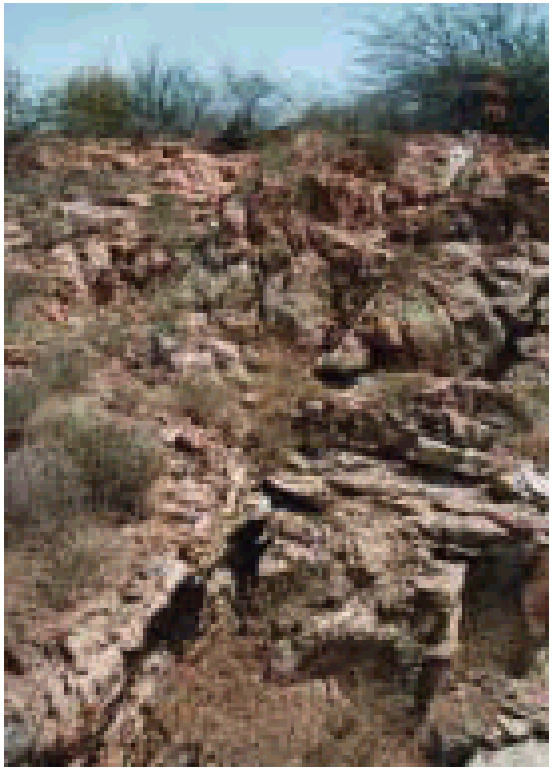


Figure 8 A perceptive view of the estimated fault plane from aftershock data



Picture towards east

Striations on the thrust fault plane (picture towards north

Figure 9 A thrust fault with striations at the northern embankment of Rudramata Bridge embankment of the Rudramata Bridge. At the same location, the bedding planes of sandstone abruptly steepens. From the striations on the fault plane and bedding planes, the inferred mechanisms of earthquakes would look like as shown in Figure 10. The strikes of faults and bedding planes at this location are similar to the general trend of the strike of the Kutch mainland fault described in the previous sections. The fault plane solution for this thrust fault strikingly is similar to that of the main shock given by various institutes.

Many ground breaks were observed during site investigations. There were three groups of ground ruptures, namely, NE, NW and NS ground breaks according to the general trend of their strikes. While NE and NW striking ground breaks had a sinistral sense; the NS striking ground breaks did a dextral sense. The southern block associated with NE and NW striking ground breaks moved upward. As for the NS ground breaks, the western block moved downward.

Nearby Bridge on Kankawati River (7km to Halvad and 100km East from the USGS epicenter), tension cracks in the ground with a strike of N75E were observed. At the southern side of the Hadakia Creek Bridge, an en-echelon crack with a length of 200m was observed and its strike was N70E. The second ground break was observed at the location 23º 32’ 59”N;70º 17’ 50”E (13km NW from the USGS epicenter). The location is 5km North of Momaymora and the orientation of the break is NW88/82. On the way from Chang Dam to Bachau near Manfera village, ground breaks with a length of 2-3km was observed. The location was is 23º 27’ 00”N;70º 22’ 00”E (17km NW from the USGS epicenter). The dip direction and dip are SW60/80. The East side of the ground break was up and the west side was down. From the sense of movement along the ground breaks, it was inferred that the ground breaks had a dextral sense. At this side there was a 16cm relative horizontal movement and 10cm vertical throw. In the Rudramata dam reservoir, some bulging of sandstone layers were observed in the direction of NS with a strike of EW. However, the cause of bulging was not well understood.

Ground breaks were observed at a location along the roadway between Anjar-Bachau. Two crack sets were observed having strikes of N40W and N40E. The locations was 23° 09' 55"N;70° 08' 27"E (48km SW from the USGS epicenter).A ground break with a strike of N75W was observed on the roadway between Bachau and Bhuj. The location is 23° 20' 30"N;70° 18' 31"E (9km SW from the USGS epicenter).

A set of parallel ground breaks near Chobari on the roadway between Momaymora and Chobari and in the adjacent fields was observed (Figure 11). Their strike was N85E. South block is up with a vertical throw of 20cm and 10cm horizontal offset. The sense was sinistral. The inferred faulting mechanism shown in Figure 12 was obtained for this set of ground breaks by assuming that fault plane is dipping towards south with an inclination of 50°. It is quite interesting that the fault plane solutions are quite similar to those obtained by various institutes.

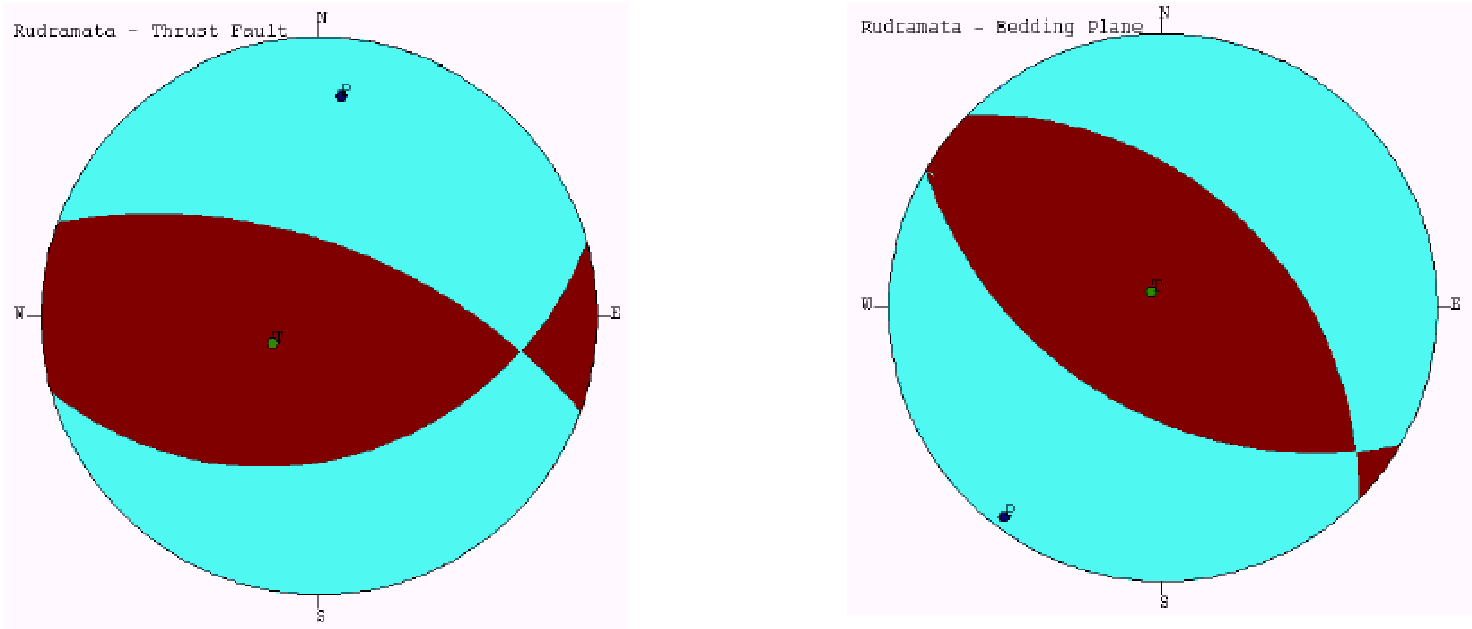


Figure 10 Inferred fault plane solutions for a thrust fault and bedding planes with striations at the northern embankment of Rudramata Bridge

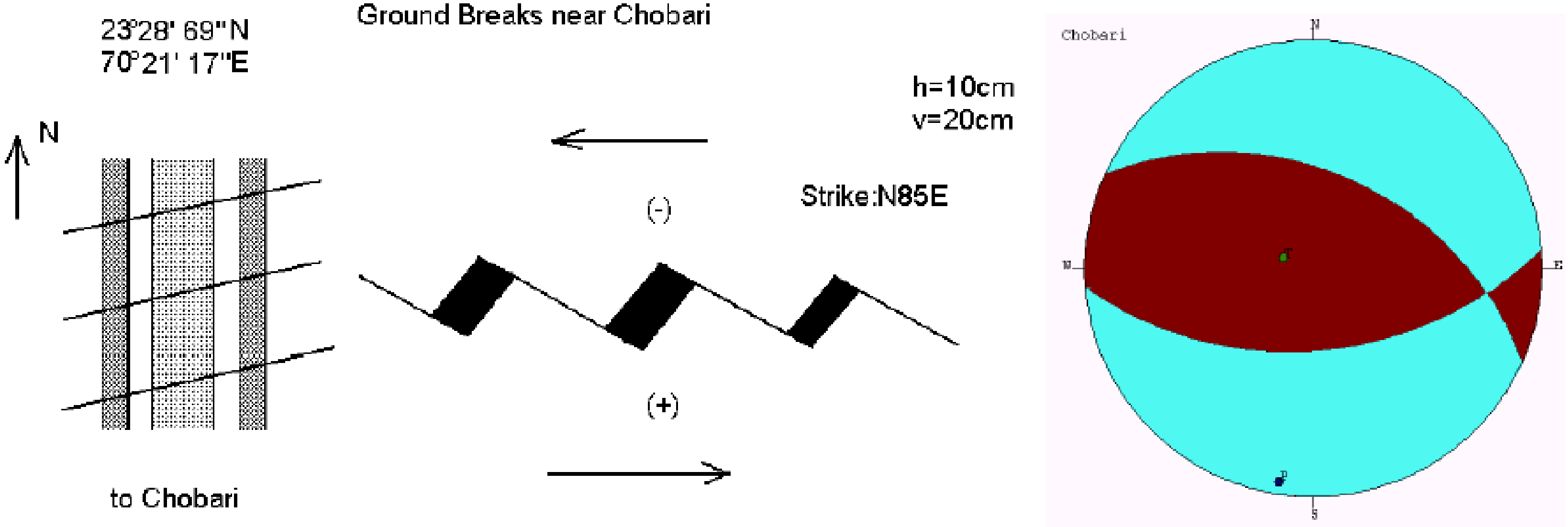


Figure 11 Sketches of ground breaks near Chobari village and its fault plane solution

A very long ground rupture was observed on the road and ground near the Trisuns chemical complex. The upward movement of the southern block was about 10cm together with a laterally sinistral sense of movement. The site is about 10.3km far from the USGS epicenter and 16.1km from the reported fault break by Oyo-corporation. The direction of the ground break was N60W. The location was 23° 18' 49"N;70° 21' 23"E. The inferred faulting mechanism obtained for this set of ground breaks by assuming that fault plane is dipping towards south with an inclination of 50° was quite similar to those obtained for the aftershock on January 28, 2001 by various institutes. Another ground break on the same roadway had the direction of N70E, which has the similar strike of the USGS fault plane solution. The location is 23° 20' 36"N;70° 17' 26"E (10km SW from the USGS epicenter).

There was a huge broad rupture zone with at least 100m width and extending for about 1.5km about 3km from the Bodarmora village. Furthermore, many small steps of the ground could be easily noticed. The southern block seems to be uplifted. The uplift movement for a single break was about 60cm with 10-14cm horizontal slip in a sinistral sense. The blocks bounded by ground breaks were tilted and the tilted plane has the dip direction and dip as SW6/34 while tension ground breaks had the dip direction and dip as NE6/74. A team of Oyo Corporation geologists more extensively investigated this location and they reported many interesting observations. They found some pressure ridges, subsidence, liquefaction and bulged zone in this location. Furthermore, the ground surface rises towards south in a step-like manner, implying similar type ground deformation during earthquakes in the past.

6 GROUND MOTION AND SEISMIC INTENSITY

It seems that there is a strong motion network established by Earthquake Engineering Department of Roorkee University in Gujarat State. So far the strong motion records observed in Ahmedabad, Delhi and Roorkee stations are only available on the web page of Earthquake Engineering Department of Roorkee University. The strong motion records obtained from the region at the Passport Office Building in Ahmedabad City indicated a peak ground acceleration of about 0.11g. The peak ground acceleration in Bombay was 50gal (personal communication Prof. Sinha of Bombay Institute of Technology). The peak ground accelerations in Delhi and Roorkee were 7gal and 4gal, respectively. The records at Bachau and Bhuj would be very valuable to know the ground motions in the vicinity of the epicentral area. Ahmedabad City, which was approximately 210km from the earthquake epicenter, experienced very high ground acceleration. From the well-known attenuation relations, the expected peak ground acceleration from attenuation relations should be less than the ones observed. The cause of high peak ground acceleration may be associated with the peculiar geological structure of Ahmedabad basin (see Figure 4). The situation resembles to that of Mexico City in 1970.

Narula and Chaubey conducted macro-seismic surveys for the Kucth earthquake and their results are summarized as follows. The reconnaissance surveys were conducted between the 3rd and 10th Feb 2001 which included an air reconnaissance followed by long traverses to assess the general damage patterns, terrain changes brought about and to look for ground rupture. The preliminary isoseismals were obtained by utilizing the MSK scale (Medvedev-Sponheuer-Karnik). The reconnaissance surveys have indicated that intensity X has been reached in an elliptical tract of about 2100 sq.km, which is characterized by complete destruction of adobe, brick and stone masonry buildings and many RCC buildings have suffered grade 4 to grade 5 damages; wide ground fissures and collapse of low height road embankments. This epicentral tract includes villages of Jawaharnagar, Dudai, Adoi, Chobari, Manfara, and Rapar. The long axis of this epicentral tract is aligned in ENE-WSW to E-W direction with maximum damage concentrated near its northern and southern boundaries. During the reconnaitory surveys only the southern boundaries of the isoseismals IX, VIII and part of VII could be constrained and the eastern, western and northern boundaries are tentative because complete area could not be traversed during the time frame of investigation. These will have to be verified by more detailed surveys. Their preliminary isoseismal map is shown in Figure 12.

The distribution of intensity VII is quite interesting and has deviated from the general E-W elongation, consistent with higher isoseismals, to almost north-south pattern along the area occupied by deep seated Quaternary and Cenozoic cover sediments along the Cambay Graben. The accentuation of the motions because of this thick cover has resulted in modification of boundaries of isoseist VII. In all the isoseists there were isolated areas of lower or higher intensities depending upon the geotechnical characteristics of the ground. One such conspicuous area is the township of Limbdi located within isoseist VII that shows damages similar to those of isoseist VIII.

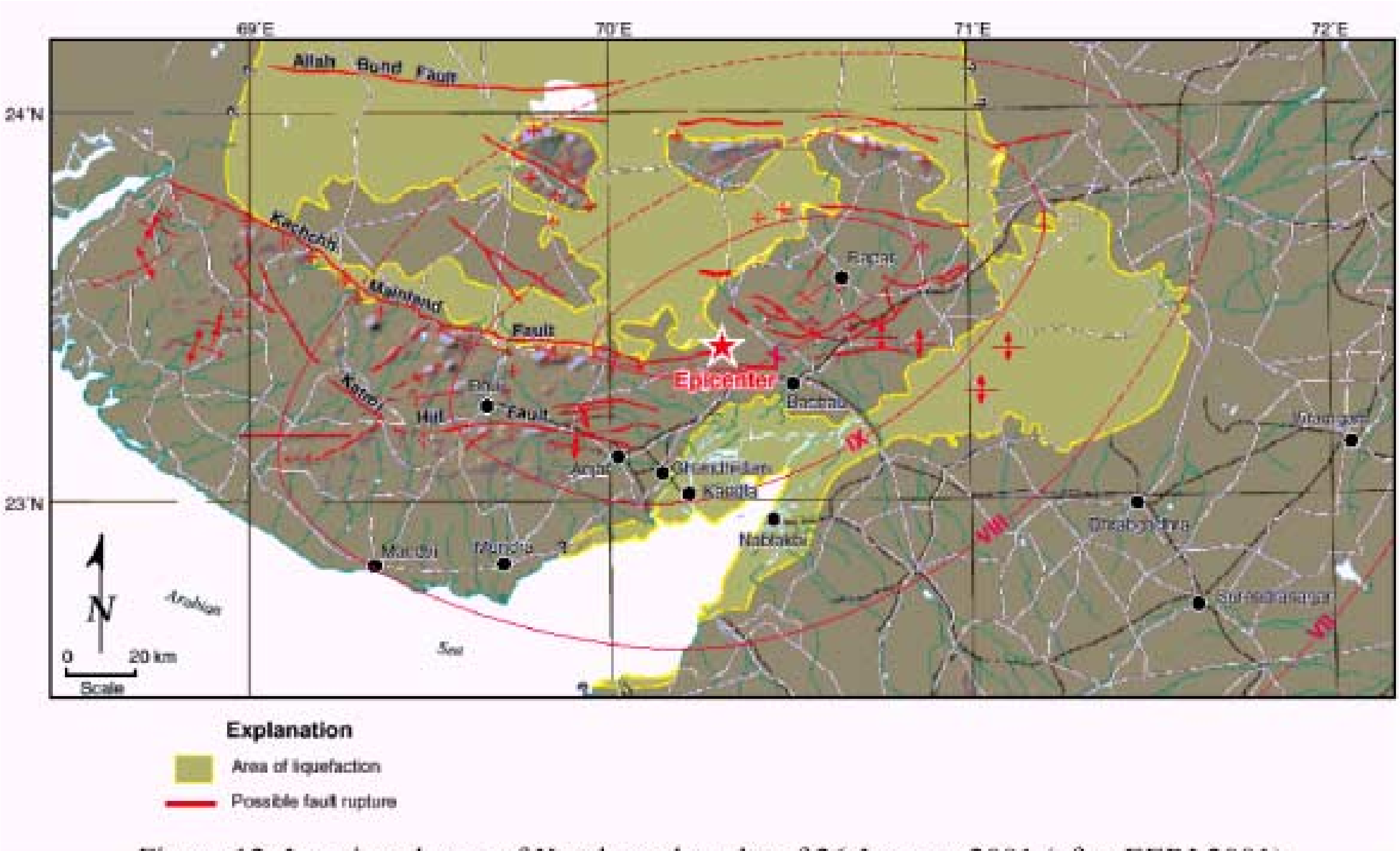


Figure 12: Isoseismal map of Kutch earthquake of 26 January 2001 (after EERI 2001).

7 DAMAGE TO STRUCTURES

7.1 Damage to Dams

Most of the dams are earthen dams except a few, which is stone masonry, built. The dams are built for irrigation purposes. There are more than 174 earth dams in the region. Seven medium sized dams and 14 small sized dams in Kutch were damaged. The major dams, which were damaged during the earthquake, were Chang, Tapar, Suvi, Shiviakha, Kaswati and Rudramata dams. Most of the dams failed or damaged at their old river course sections. The reason of the failure or damage was associated with the liquefaction of sub-soil below the embankment of the dam. Figure 13 shows views of damage to Suvi and Chang dams.

(a) Chang Dam

(b) Suvi Dam

Figure 13 Views of Failures of Chang and Suvi dams

7.2 Damage to Port Facilities

The Kandla Port was built in 1955. No crane is toppled. The Port Building on the piles near the main gate tilted with an inclination of 1-2 degree. The Kandla port is aligned in the direction of NS. Berths No.1 to 5 at Kandla Port have developed some major structural damage. Berths No.6 to 9 are functional. The strong shaking damaged many piles supporting the docks of berths No.1 to No.5. The piles were cracked by the bending, and some concrete pieces were chipped from the pile tops. The pile length is about 20m below the frame structure and the diameter is 60cm. The cracks on the piles are not severe as shown in Figure 14. However, they have to be repaired with the steel plate or carbon fiber jacketing in order to protect the steel bars from the corrosion.

The old jetty of the port on the piles with a length of 15m is shifted towards the sea. The top of piles had small hair cracks. Furthermore, the settlement of filled section of the port was about 7cm. The jetty of the oil-pipelines at Kandla port was heavily damaged due to breakage of the piers (Figure 15). The piers were almost ruptured at their mid.

Figure 14 Cracking of piles at Kandla port

Figure 15 A view of damaged oil jetty at the Kandla port on March 19, 2001.

7.3 Damage to Transportation facilities

Damages to railways can be classified as follows: damage to railway tracks, signal & telecommunication system, electrical facilities, stations and bridges. Damage to railway tracks was observed in the form of bending and distortion of rails and tracks due to ground shaking and deformation. This situation could be clearly observed at Gandhidham railway station. There were three railway lines. Two of them were under construction. It was apparent that some rails were bent or were offset although they were repaired after the earthquake. 20 railway stations across Kutch were damaged as a result of the earthquake. Gandhidham station was the worst hit. Gandhidham railway station was an RC structure and some structural damage to the railway station was observed. It was also reported that an accident took place on the railway due to de-railment of a train at Ratnal.

Out of 650 Kms of highways, 100 Kms severely damaged. Most of roadways had to be re-surfaced due to extensional and bulging type cracking (Figure 16). Furthermore, the embankments of bridges settled and caused the slow down of the traffic (Figure 17). In some places, the traffic had to be diverted for the repairment of embankments. The tollgate buildings of the highway 8A were broken at their base columns (Figure 17).

Railway bridges were almost non-damaged. At a railway bridge 7km from Halvad (100km from the USGS epicenter) there was no visible damage while some damage to roadway bridges at the same location was observed. The only reported damage occurred at Bridge No.48 between Kukma and Bhuj and it was restored on 3rd Feb., 2001.

(a) Bachau-Bhuj roadway　　(b) Roadway to Manfera

Figure 16 Damaged roadways due to ground deformation

Figure 17 Damage to toll gates and settlement of bridge embankments

Most of the minor/major roadway and highway bridges in Kutch region were damaged. Parapets of the minor and major bridges were totally or partially toppled or displaced in the entire region affected by the earthquake. The settlement and lateral spreading of ground particularly affected the piers of Hadakia Bridge and Rudramata Bridge. The soil at both sides of the bridge abutments settled and spread towards the center of the valley (Figure 18).

Figure 18 Rudramata bridge

7.4 Damage to Industrial Facilities

7.4.1 Electricity and Power Plants

There are three thermal power plants, namely, Panandro TPP, Ahmebabad TPP and Mahesana TPP. These thermal power plants burn lignite and they were non-damaged during the earthquake. The earthquake led to a tripping of various power plants including the 1200 MW Wanakbori, 450 MW Gandhinagar, 280 MW Dhuvaran, 111. MW Panandro, 11.0 MW Sikka, 90 MW Gandhar and 380 MW AECO plants, resulting in a total generation loss of 2600 MW.

The 370 MW lignite (coal) burning plants located in Panandhro about 180 km northwest of the epicenter and they experienced only minor cracking. The supply is supplemented by a coal-burning plant in Ahmedabad, 211. km east of the epicenter. In Gujarat State, the Kakrapar nuclear power plants Unit No.1 (220MW) and No.2 were in operation at the time of the earthquake, which was located about 400km southeast of the epicenters. The Kakrapar nuclear power plant suffered no damaged and it did not stop supplying power just after earthquake.

The Gujarat Electricity Board is supplying power to all the town and villages through a network of 3,2 and 40 number of 220 KV,132 KV,66 KV sub-stations respectively and by 225 number of 11 KV feeders. Three 220 KV sub-stations are located in Anjar, Nanikhakhar and Nakhatrana. One 132 KV sub-station is located at Samakhiyali. The electricty of Indian System is as follows: 400kV → 220kV → 132 kV → 66kV → 11 kV → 440V → 220V. Frequency is 50Hz

Power is transmitted from Panandhro, through 220 kV and 132 kV systems, southeast through the region. Over a dozen substation control buildings collapsed, and a total of 45 were damaged. The control building damage had the greatest impact on the overall system failure. Pylons were almost non-damaged in the earthquake area even some of them passed through the marsh lands and salt playas. but some of them passes through salt playas experienced some damages. Figure 19 shows the damage of the pylon foundation in salt playas near Hadakia Bridge. The foundation moved and about 11 cm wide gaps occurred between the pile-foundations and the surrounding ground, and the concrete beams which connected the pile foundations experienced some cracks.

In the Anjar 220 KV substation, the communications system and power protection system had failed when the battery rack collapsed. They could not enter the control building because of concerns about collapse of the roof. The unanchored control panels inside did not topple. In the yard, all transformers derailed, some bushings broke (Figure 20). Four circuit breakers had failed porcelain insulators (Figure 20). The first major substation was brought back online on 1/29 in Bhuj (132 kV), and the first 220 kV substation brought back on line in Anjar on 1/30. As of 2/5, an estimated 80% of the region's power had been restored.

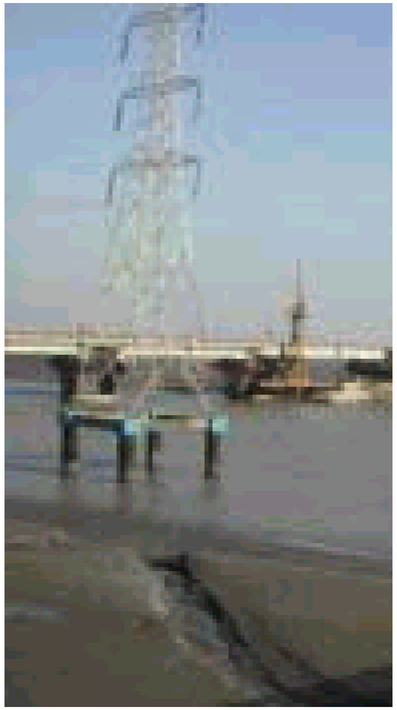


Figure 19 Damaged pylons near Hadakia Bridge


Figure 20 Displaced transformers and damaged breakers at Anjar sub-station

7.4.2 Oil Tanks

Tanks at Friends Tank Firm, Oil India and Trisuns Chemical Plant were checked. There are 66 cylindrical tanks having a diameter ranging between 7-26m at Friends Tank Farm. The pump houses were RC type and had structural damage. No damage to pumps was reported. The tank yard is built on a reclaimed land. The topsoil was excavated to a depth of 2m after constructing an all-around wall and drained. Then lateritic soil with poor grading was filled to a height of 3.5m. After compaction, tanks were built over this soil basement.

Two tanks were heavily tilted and connections of valves to pipelines were damaged due to tilting and sinking of the tanks (Figure 21). It seems that the tilting and sinking were due to foundation failure associated with the base soil. Considering the bulging and motion of the ground, it seems that the ground moved in the direction of S40W-S50W. Besides the two heavily tilted tanks, some differential settlements, tilting and sinking of the tanks were observed in the newly reclaimed tank yard. In oil tank yard, which was built for more than 20 years ago, the settlement of the ground was not observed.

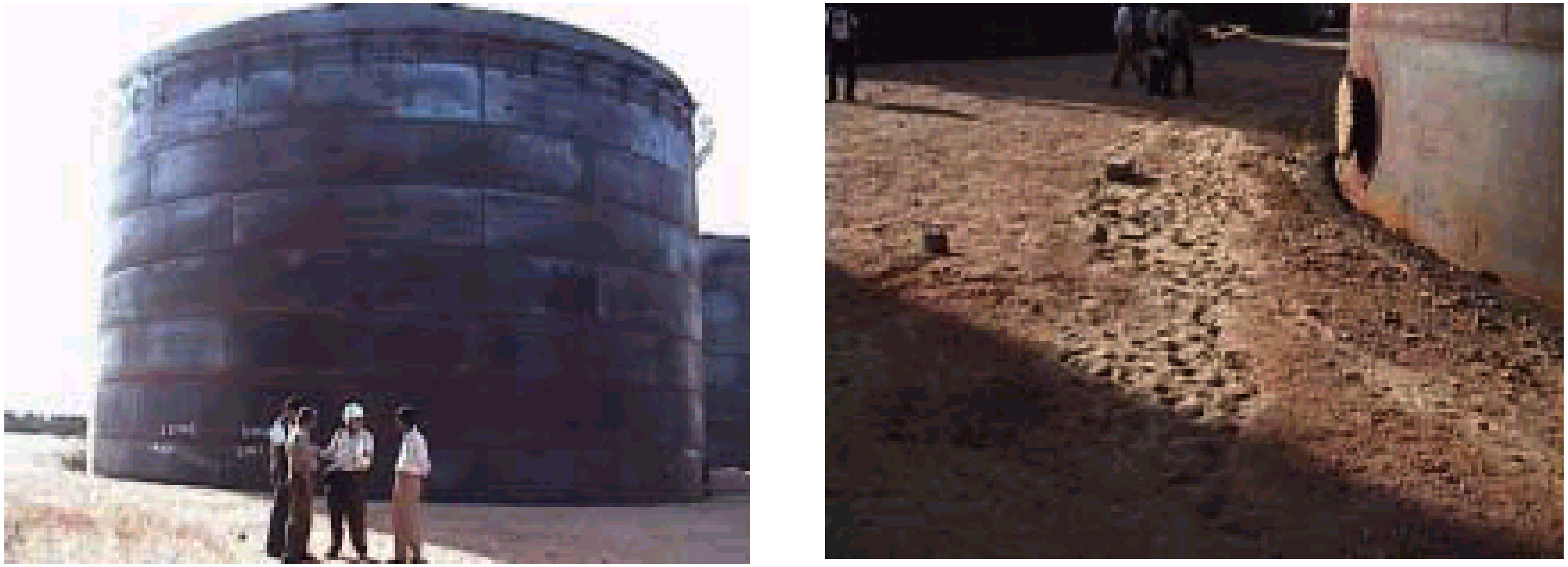


Figure 21 Tilted and damaged tanks at the Friends Tank Farm

Most of tanks were non-damaged in the Tank farm of Oil India (Figure 22(a)). Nevertheless, some oil tanks were buckled or tilted. Some of damage to tanks was due to the liquefaction of the foundation soil. There were 6 steel tanks with a conical fixed roof. No damage to tanks was observed although it was very close to the epicenter of the earthquake (Figure 22(b)). The tanks had 2m thick concrete basement. The buildings in this complex, however, were heavily damaged. One of storehouses was completely collapsed while the roofs of other storehouses were partially collapsed.

(a) Damaged Tanks at Oil India

(b) Non-damaged oil tanks at Trisuns Plant

Figure 22 Damaged and non-damaged tanks

7.4.3 Pipelines

Product pipelines from Vadinar to Kandla & Kandla to Bhatinda were shutdown. The pipe racks made of steel and were bent or buckled in the vicinity of the port. There was no breakage of the pipelines at any location although they were displaced from their original locations. The steel stripe type fixtures were either broken or separated from their welding locations (Figure 23(a)). The pipes were displaced both laterally 30cm and longitudinally 40cm. The direction of movement was NE towards the epicenter. The liquefaction and lateral movement of the ground was observed at the base of pipelines as shown in Figure 23(b). Crude oil pipelines from Salaya, feeding Koyali/Mathura/Panipat refineries resumed operations since 27th Jan after due checking. The oil pipelines from the Kandla Port were severely damaged (Figure 23(c)). The pipelines are supported by the two layer steel frames and each frame supports three pipelines (Figure 23(d)). Two of them were filled with oil during earthquake. The pipelines are running to the NS direction and the south ends are curved to the west direction. Because the ground motion of the NS direction was dominant and the shaking modes were different for the three parallel pipelines, which have different curvatures, the steel frames were buckled and collapsed with the pipelines.

(a)

(b)

(c)

(d)

Figure 23 Damage to pipelines

8 LIQUEFACTION AND LATERAL SPREADING

Widespread liquefaction was observed in the Rann of Kutch, the Little Rann of Kutch as well as the coastal areas of the Gulf in the vicinity of Ghandidham, Kandla, and between Malya and Samakhiali. Liquefaction was widespread particularly along the seashore, riverbeds, ponds and marshland and salt playas. The liquefaction has manifested along long fissures and at many places it is of vent type (Figure 24(a)). This phenomenon was responsible for failure of some embankments in the mesoseismal area. In the coastal areas and dam reservoirs evidences of lateral spreading were also observed. Some embankment failures and traces of liquefaction and lateral spreading of ground were observed at distances more than 100km from the epicenter such as nearby the Bridge over Malia Creek and Kadhan in Pakistan.

The bridge was severely damaged due to the liquefaction and its induced ground displacement. Numerous sand vents could be observed on the river bed in the neighborhood of the bridge as shown in Figure 24(b). The evidences of liquefaction-induced ground displacement were found on the riverbed. And the concrete piers with caisson foundations moved toward the river center due to the ground displacement as shown. The bridge also suffered considerable subsidence of foundations caused by liquefaction and the transportation function was lost after the earthquake.

(a) Dhori　　(b) Hadakia Bridge

Figure 24 Some examples of liquefaction

Some lateral spreading of ground was observed within the Suvi dam reservoir. This may be due to soil liquefaction as quartzitic sand with a repose angle of 32 degree is observed along the cracks. The slumped section of this dam was also thought to be the result of liquefaction of soil at the base of the dam.

Although the base rock of the Chang dam was mudstone with almost horizontal layering, the old river course may be consisted of sandy material. In the upstream side the sand boiling can be clearly observed even more than 50 days passed over the earthquake (Figure 25(a)). It seems that the failure of the dam is due to liquefaction at its base and it resembles to the failure of San Fernandes dam. Furthermore, some lateral spreading could be observed at many locations around the reservoir (Figure 25(b)).

Liquefaction observed within the Kandla port and its vicinity. Although the effect of liquefaction on port facilities was quite small, there were several examples of liquefaction. Liquefaction was also observed at Navlakhi port in the Kathiawar peninsula and Advani port in Mundra along the coast of Arabian Sea.

(a)

(b)

Figure 25 Liquefaction and lateral spreading at Chang dam

Wide spread lateral spreading of ground was observed at both sides of the valley of the Rudramata Bridge. The soil at both sides of the settled and spread towards the center of the valley. Cracks run along the longitudinal axis of the valley. The crack on the south embankment was mistakenly interpreted as the fault break. The crack is due to the lateral spreading of the ground (Figure 26).

Figure 26 Settlement and lateral spreading in the vicinity of Rudramata Bridge

Figure 27 shows the grain size accumulation curve of the boiled-out sands at Kandla port, Chang dam and Chobari with the sand from Niigata City. The samples mostly consisted of liquefiable fine sands with mean grain sizes of 0.15～0.30mm, respectively.

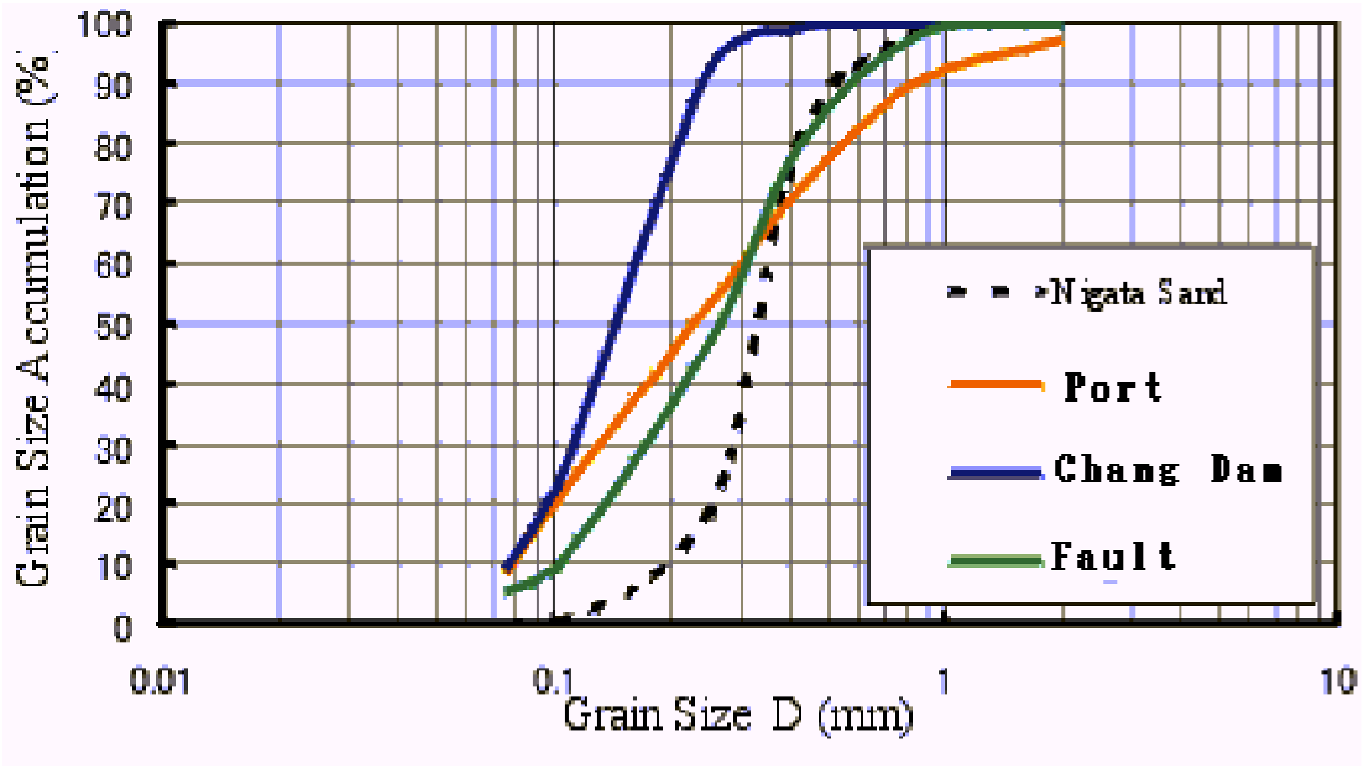


Figure 27 Grain size accumulation of the boiled-out sands

9 BUILDINGS AND ELEVATED TANKS

9.1 Buildings

Buildings in the affected area can be classified into two broad categories:
(a) Masonry buildings, and
(b) Reinforced concrete buildings.
Masonry buildings may also sub-divided into several categories such as:
(a) Adobe type buildings
(b) Burned brick buildings
(c) Random or cut stone buildings with mud, lime or cement mortar.

Masonry buildings have either cylindrical or rectangular in plan. The cylindrical masonry buildings are called either traditional Kutch houses or Bhonga. During the earthquake, the Bhongas suffered varying extent of damage depending on their age and construction technology. In the epicentral region, the traditional adobe Bhonga constructions suffered significant damage due to the collapse of walls and failure of conical roof. The roofs generally collapsed due to failure of vertical post. Most Bhongas collapsed on the outside and resulted in very low casualties. The Bhongas constructed from brick masonry and cement mortar suffered only minor damage.

Most of dwellings made of mud mortar either totally collapsed or heavily damaged. The damage rate was quite high near the epicentral area, particularly, Bachau, Anjar, Lilpar, Chobari, Ratnal and the old city of Bhuj within the fort. Figure 28 show several examples of the heavy damage to masonry structures with mud mortar. On the other hand, if masonry buildings are constructed using mortar is lime or cement mortar, they performed much better and the total collapses were much less as seen in the same figure. Most of the standing masonry buildings in the pictures are such structures. Especially, the use of cement mortar together with well-spaced concrete slabs improved the integrity of the buildings.

The reinforced concrete frame buildings are generally constructed with the use of unreinforced masonry infill walls. The infill walls are 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.

Among the cities affected in the area are, Many modern reinforced concrete multi-story buildings collapsed in two densely populated metropolitan cities of Ahmedabad and Gandhidham. Among the multi-story buildings that collapsed, most had the ground story left open for parking convenience with few or no filler walls between the columns. Most buildings with complete infills in the ground story have withstood the earthquake without collapse. Some of causes of damage to reinforced concrete buildings in Ahmedabad City (210km away from the USGS epicenter) as well as in other cities and towns are as follows (Figures 29 & 30):

a) Long duration of shaking (about 90 seconds)
b) Damage was concentrated to areas that the land was re-claimed and buildings were new
c) The number of stories of buildings ranged between 4 and 5.
d) The top soil was sandy clay with sand soil below,
e) Collapsed buildings had isolated footings and the footings were not connected to each with lateral tie beams.
f)Constructors did not flow the earthquake design code
g) Collapsed buildings were mostly pivoti type and no shear walls at ground floor
h) Ground amplification due to geological structures such as in Anjar and Ahmedabad
i) Poor workmanship
j) Rusting of steel bars due to the use of saline sand and gravel

Figure 28 Examples of damage to masonry buildings in Bachau and Lilpar

Figure 29 Partially collapsed Mansi Apartment Complex in Ahmedabad and its footing

Figure 30 Collapsed Apartment blocks are ground floor in Bhuj

9.2 Elevated Water Tanks

Many of the systems have elevated concrete storage tanks that are on the order of 30m high (Figure 31). Most of the water tanks, which are elevated, did not suffer any substantial damage although severe damage could be observed at nearby buildings and structures. The water tank at Chobari village was toppled (Figure 32). The water tower was fallen in the direction of S30E. The location is 23° 31' 22"N;70° 20' 64"E. The water tank in Bachau town also survived the earthquake. The water tank in Anjar was an RC structure with four piers and built in 1955 with a capacity of 20000 gallons. It seems that there is more 250 water tanks in the region. However, 5 elevated tanks failed in the Malya-Morbi region south of the Gulf of Kutch. All the tanks are designed in the same state office. However, it is unclear why the failures in the Malya-Morbi area would have occurred and this deserves further investigation.

Figure 29 Non-damaged typical elevated water tank in Bachau

Figure 30 Collapsed water tank in Chobari village

10 CONCLUSIONS

The authors presented an overview of the investigation by the JSCE team on the 2001 West India earthquake covered various aspects of the earthquake. Specifically, the geology, tectonics and seismicity of the earthquake region, characteristics of strong motion records, damage to buildings, infra-structures, geotechnical structures and lifelines have been are described. The detailed outcomes of the investigation are presented and discussed in each chapter of this report to be published by the Earthquake Engineering Committee of the Japan Society of Civil Engineers. These outcomes and conclusions may be briefly summarized as follows:

- Although it is generally accepted that the Indian plate is stable and seismic activity take places along the plate boundaries with other plates, there are also some earthquakes within the Indian plate, which implies that the Indian plate is not perfectly rigid. The 1819 Allahbund earthquake (M8), 2001 Kutch earthquake (M7.9), 1993 Latur earthquake (M6.3), 1997 Jabalpur earthquake (M6) and 1970 Broach (M5.4) indicate that great intra-plate earthquakes may also occur in Indian plate.
- The seismic records on the previous day (January 25, 2001) obtained by the Bhuj seismological observation station during a visit on March 21, 2001 indicated that there was not any foreshock while there were numerous aftershocks following the mainshock.

- The aftershocks are scattered around the USGS epicenter and the distribution of aftershock data seems to confirm the fault plane solutions obtained by four different institutes. Since there was not any well-defined fault scarp on the ground surface, it is difficult to say which of the fault planes determined from the fault plane solutions corresponds to the causative fault. Nevertheless, the fault plane with the NE strike and dipping south could be the causative fault of this earthquake in view of the spatial distribution of the aftershocks and widely scattered surface ruptures.
- Widespread liquefaction was observed in the Rann of Kutch, the Little Rann of Kutch as well as the coastal areas of the Gulf in the vicinity of Ghandidham, Kandla, and between Malya and Samakhiali. Liquefaction was widespread particularly along the seashore, riverbeds, ponds and marshland and salt playas. The liquefaction has manifested along long fissures and at many places it is of vent type. However, the structural damage due to liquefaction was quite limited in-spite of the huge scale of liquefaction.
- Most of the dams are earthen dams except a few, which is stone masonry, built. The dams are built for irrigation purposes. The dam failures were associated with the liquefaction of sub-soil along the old river course.
- Damage to railway tracks was observed in the form of bending and distortion of rails and tracks due to ground shaking and deformation. 20 railway stations across Kutch were damaged as a result of the earthquake. Gandhidham station was the worst hit. Gandhidham railways station was an RC structure and some structural damage to the railway station was observed

- Most of roadways had to be re-surfaced due to extensional and bulging type cracking. Furthermore, the settlement of embankments of bridges caused differential settlement and slows down of the traffic.
- Railway bridges were almost non-damaged. The only reported damage occurred at Bridge No.48 between Kukma and Bhuj and it was restored on 3rd Feb., 2001.
- Most of the minor/major roadway and highway bridges in Kutch region were damaged. Parapets of the minor and major bridges were totally or partially toppled or displaced in the entire region affected by the earthquake.
- The structural damage to Kandla, Navlakhi Ports was minor. No crane is toppled at the Kandla port. The Port Building on the piles near the main gate tilted with an inclination of 1-2 degree. Berths No.1 to 5 at Kandla Port have developed some structural damage. Berths No.6 to 9 are functional. The strong shaking damaged many piles supporting the docks of berths No.1 to No.5. The piles were cracked by the bending, and some concrete pieces were chipped from the pile tops.
- The 370 MW lignite (coal) burning plants located in Panandhro about 180 km northwest of the epicenter and they experienced only minor cracking while there was no damage to a coal-burning plant in Ahmedabad, 211. km east of the epicenter. The Kakrapar nuclear power plants Unit No.1 (220MW) and No.2 in Gujarat State were in operation at the time of the earthquake, which was located about 400km southeast of the epicenters. The Kakrapar nuclear power plant suffered no damaged, and it did not stop supplying power just after earthquake.

- Pylons were almost non-damaged in the earthquake area even some of them passed through the marsh lands and salt playas. but some of them passes through salt playas experienced damages
- In the Anjar 220 KV substation, the communications system and power protection system had failed when the battery rack collapsed. In the yard, all transformers derailed, some bushings were broken.
- Oil and chemical tanks were almost non-damaged. Damage to tanks mostly resulted from the settlement of foundation ground due to liquefaction.
- The stoppers or racks of the pipelines were either broken or buckled in the port area.
- Most of dwellings made of mud mortar either totally collapsed or heavily damaged. The damage rate was quite high near the epicentral area, particularly, Bachau, Anjar, Lilpar, Chobari, Ratnal and the old city of Bhuj within the fort.
- On the other hand, if masonry buildings are constructed using mortar is lime or cement mortar, they performed much better and the total collapses were much less.
- Many modern reinforced concrete multi-story buildings collapsed in two densely populated metropolitan cities of Ahmedabad and Gandhidham. Among the multi-story buildings that collapsed, most had the ground story left open for parking convenience with few or no filler walls between the columns. Most buildings with complete infills in the ground story have withstood the earthquake without collapse.

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REFERENCES

Banerjee, A., Jha, M., Mittal, A.K., Thomas, N.J., Misra, K.N. (2000): The effective source rocks in the north Cambay basin, India. Marine and Petroleum Geology, 17, 1111-1129.

Biswas, S. K.(1987): Regional Tectonic Framework, structure and evolution of the western marginal basin of India, Tectonophysics, 135, pp.307-327.

Jain, S. K. & Lettis, W. R. (2001): Preliminray observations on the origin and effects of January 26, 2001 Bhuj(Gujarat,India) Earthquake, EERI Special Earthquake Report, April 2001.

Malik, J.N., Sohoni, P.S., Merh, S.S., Karanth, R.V. (2000): Active Tectonic control on Allu Architecture along the Kachchh Mainland Hill Range, Western India, Zeithschrift fur Geomophology.

Narula, P.L. & Chaubey, S.K. (2001): Macroseismic surveys for the Bhuj(India) earthquake of January 26, 2001. http://www.nicee.org/NICEE/Gujarat/narula.html

OYO Corporation(2001)：January 26, 2001 India-Gujarat Earthquake Damage Investigation Report (in Japanese) : http://www.oyo.co.jp/service/taisyou/jisin/indo/index.html

Yagi, Y. and Kikuchi, M.(2000): Result of Rupture Process for January 26, 2001 Western India Earthquake (Ms7.9), http://wwweic.eri,u-tokyo.ac.jp/

USGS: http://neic.usgs.gov/neis/eqhaz/010126_int.html