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# The recent seismic activity in Gujarat region (Western India)

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## Abstract

The Jan. 26, 2001, Mw=7.7 earthquake occurred in Gujarat region of W. India, which lies 200-400 Km away from the active plate boundary zone, between the Indian subcontinent and the Asian plate, along the India-Pakistan border and the Himalayan belt. A zone of co-seismic E-W surface ruptures, 30-40 Km long and 15-20 Km wide, observed near the epicentral area and seems to be associated with pre-existing reverse faults and thrust folds, which were partially reactivated during the recent earthquake. Except the reverse vertical displacement a significant right lateral displacement was also observed along these E-W surface ruptures. This Ms=7.7 seismic event has been also accompanied by a large scale flexural-slip folding, as the absence of significant co-seismic fault displacement and fault scarp shows. The NW-SE open cracks, also observed along the same zone, are associated with the right lateral horizontal displacement of the reactivated fault (or branch faults) and the development of local extensional stress field in the huge anticlinic hinges of the co-seismic flexural-slip folds. A grate number of ground ruptures, failures and open cracks are also associated with extensive sand boils, liquefaction phenomena and lateral spreading. The earthquake also produced numerous slope failures, such as rockfalls, topple failures and surficial ravelling. All kinds of constructions (buildings, bridges, ports, industrial facilities, manufacturing units) and lifelines (transportation, communications, electrical power and water supply) sustained heavy damage within the epicentral area, while different type of constructions and lifelines suffered various failures depending on the epicenter distance and the concomitant phenomena.

## 1 Introduction

On January 26$^{th}$ 2001 (at 8:46 local time) a strong earthquake stricken the Gujarat district of West India. The epicenter was detected near the Bhachau city

(23.40N, 70.32E). The magnitude of the earthquake was Mw=7.7 and the hypocentral depth was 23.6 Km (data by USGS). This earthquake was the strongest ever registered in India over the last 150 years. The strongest before that occurred almost within the same epicentral area was on June 16th 1819.

The last earthquake in Gujarat was so strong that it was recorded even in cities as far away as Bombay, Delhi, Karats which are 1500 Km from the epicenter. It was also felt in several areas in Nepal. It is worth mentioning that the stricken region is the heart of the Indian industrial area, which is the main supplier of electricity, oil refining, and steel industry, and the damages of this event are huge in relation to the income per capital of the population. The cities located at the epicentral area, such as Bhachau, Bhuj, Anjar, Kandla, have sustained complete or almost complete destruction. The city of Bhachau and several other nearby towns and villages have totally destroyed, while multistorage buildings were collapsed in cities that located in a distance more than 350 km from the epicentral zone, like as the capital of Gujarat, Ahmedabad. The Times of India reported on February 1st that there were at least 35.000 deaths, while the final estimate were around 100.000.

The epicenter of the earthquake indicates that the seismic event occurred in a stable continental region, within the Indian microplate, at a distance of 400 to 800 Km from the Himalayan belt and the active plate boundary zone, between the Indian subcontinent and the Asian plate. The major collisional processes along the Himalayan belt seems to create the suitable dynamic conditions, in the internal part of Indian microplate, for the appearance of faults (mainly thrust or strike-slip faults and rarely normal) along distinct zones, responsible for seismic activity such as in Gujarat region. It should be underlined here that for several researchers [10] the tectonic setting of the widely known area of Gujarat region is still problematic. This is because in that region appears characteristics showing both, a marginal as well as a within plate geodynamical setting. The presence of a zone with several active thrust faults and folds (also confirmed by the large magnitudes and the focal mechanisms of the earthquakes), indicates that this zone represents a transitional zone between the stable part of the Indian microplate and the margin under collision.

The aim of this study is to describe and interprate the tectonic structures and geotechnical effects occurred during this earthquake as well as to correlate these with the extensive damages in the region.

## 2 Tectonic setting and seismotectonic frame of the major area

From geological point of view [3], [4], [6], [7], the major part of the stable continental region of the Indian microplate is characterized by a Pre-Cambrian crystalline basement which is overlain by a thick Phanerozoic sedimentary sequence. This sequence consists of continental and marine sediments very often separated by characteristic unconformities due to continental isostatic movements.

As it is mentioned above the last earthquake was not the only one during the history of this region. In Kachchh (Gujarat district) a seismic event of an equivalent magnitude (7.7±0.2) also occurred in 1819. Other events of lesser

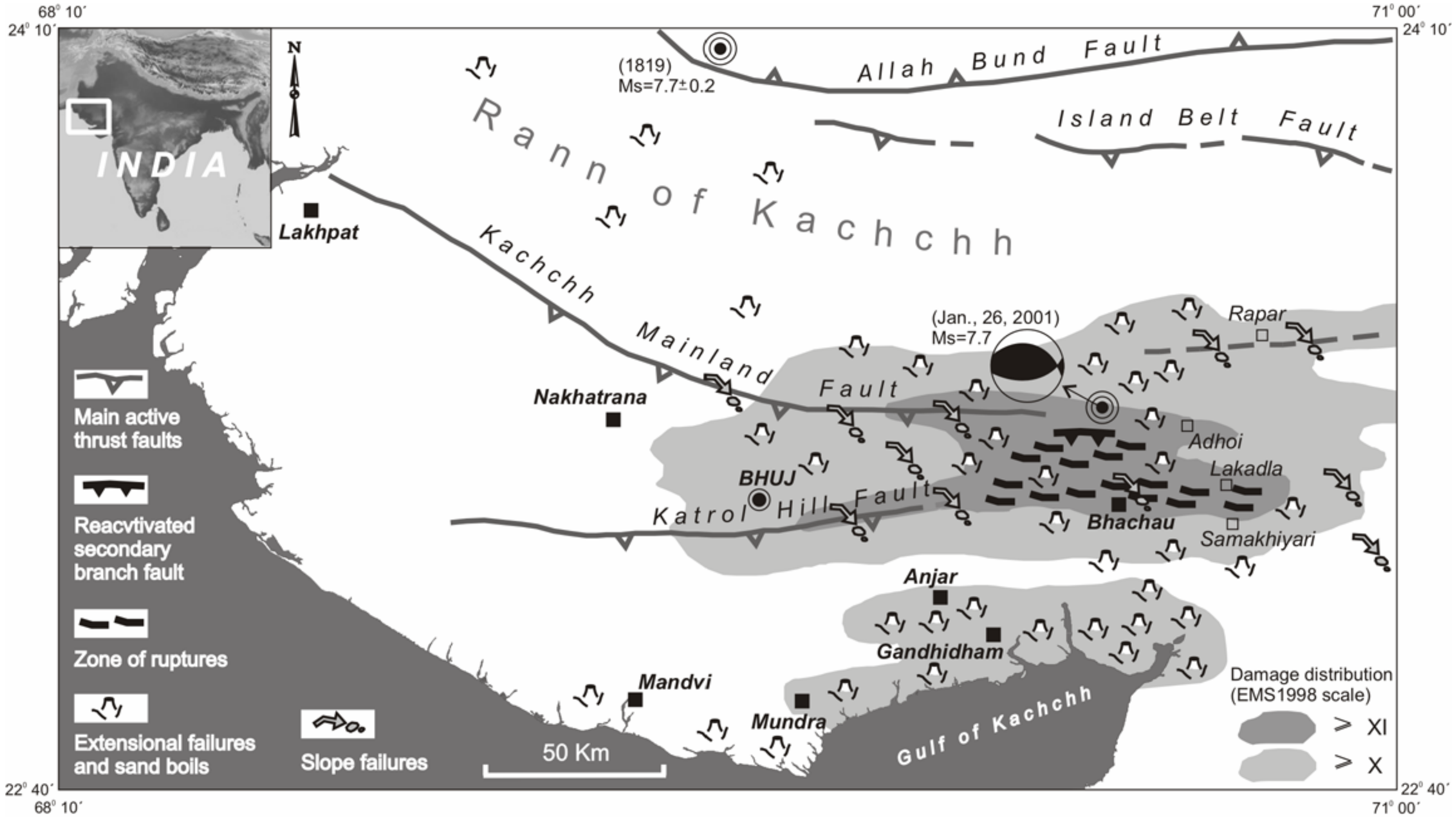


Figure. 1: Simplified map showing the tectonic structures and geotechnical effects occurred during the earthquake.

importance has occurred and caused major damage. The focal mechanisms shows thrust faults accompanied by a small scale strike-slip movement with a main E-W direction due to the northward collisional movement of the Indian plate.

The greater area of Kachchh is characterised by the presence of horizontal to sub horizontal Mesozoic and Cainozoic sediments which are folded only along the zones of high seismic activity, forming large scale open anticlines and synclines. These folds are also correlated with large scale thrust-belts with the same E-W direction [9].

From the seismotectonic point of view the greater region is bounded, northward and southward, by two major fault-zones trending to the E-W direction, known as Nagar–Parkar Fault (to the North) and Kachchh Mainland Fault (to the South). Smaller scale fault-zones with the same direction crossing the internal part of the region.

The thrust fault and fold activity within time has created a characteristic topography of a hilly region which is coming in contrast with the flattened general view of the adjacent area. Several generations of screes, talus cones and alluvial fans, as well as characteristic morphological discontinuities and Quaternary terraces crossed by deep valleys, represents some of the geomorphological structures which indicates that the topography is under the control of active tectonics. Particularly, the general morphological structures trending to the E-W direction, parallel to the main fault- and fold-zones of the area. The kinematic data from the field, which also confirmed by the geodetic data [1], [2], indicates that these fault-zones are characterized by a reverse strike slip movement, resulting to characteristic E-W tectonic grabens, like this one of Kachchh, which is bounded by the Allah Bund Fault to the North and the Kachchh Mainland Fault to the South.

It is pointed out that the Allah Bund Fault Zone produced by the earthquake of 1819 (Ms=7.7±0.2). The total length of the fault trace was 80 to 90 Km and the fault scarp in the alluvial deposits about 6-9 m. During the Anjar earthquake in 1956 (Ms=6.1) which is correlated with the reactivation of other fault-zones to the south, the fault scarp was about 1m [2], [9].

The tectonic status of the entire area is also responsible for the uplifting of large scale blocks, characterized by complex fault kinematics, resulting to the outcropping of Mesozoic rocks in their upper parts due to the subsequent erosion. The smaller scale tectonic blocks show also complex uplifting with important deformation of the sediments near the margins and less important in their internal parts. This is resulted to the formation of elliptical domes, asymmetric anticlines, large scale kink-folds, flexures, questas- and mesas-type structures, with a general E-W trend. Also, it has observed for the most of the blocks, one of their margins is been defined by a thrust fault, usually the northern one, while the other one by assymetrical open folds or flexural slip folding.

According to all these mentioned above, is obvious that the major area of Kachchh shows a continuous seismic activity, at least during the last 200 years. This activity is manifested with earthquakes with magnitudes of 3.5 to 8 of the Richter scale.

The most badly stricken region by the event of 26$^{th}$ June is the major epicentral area, situated northward from the gulf of Kachchh and covers a zone (more than 200 Km) with an E-W direction, form Nakhatrana and Bhuj in the west towards Bhachau and Rapar in the east. The most important fault-zone in this area is the Kachchh Mainland Fault trending to the ESE-WNW or E-W direction and it is more than 200 Km long. It separates the flattened area of Great Rann of Kachchh in the north, from the hilly and mountainous region of the hinterland in the south. Here is underlined that the reactivation of the eastern part of this zone seems to be related to the recent seismic event although there is no clear exposure of the fault in the surface. The focal mechanism of the earthquake indicates that the maximum displacement in the depth is about 8 to 9 m, whereas the vertical uplift about 2 m in the epicentral area (data by USGS).

Southward, two more fault-zones of smaller scale are detected with similar geometric and kinematic characteristics. The first one of these zones located south of the town of Bhuj (known as Katrol Hill Fault) and the second one is located north of Anjar city. Between these zones and towards the western part of the hilly semi-mountained area, there are few smaller faults (between 20-50km), trending mainly to the SE-NW and rarely to the E-W direction. Northward, in the region of Adhoi and Rapar, faults of a similar importance and E-W trend also observed. The trace of Allah Bund Fault which, reactivated during the 1819 earthquake, passes 100 to 150 km north of the stricken area and the kachchh Mainland Fault.

From the geometrical point of view, the most of the thrust faults in the epicentral area are almost vertical or very steep, plunging to the south with an angle of $60^0$-$80^0$. Small scale faults also observed in the major area showing the same kinematic character. In several cases these faults represent the continuation of kink or flexural-slip folds with a relevant geometry and kinematics.

## 3 Tectonic structures and geotechnical effects

The extensive research which was carried out in the greater area after the earthquake enhanced to reveal an important number of tectonic structures and geotechnical effects in direct correlation to the seismotectonic frame of the recent seismic event. These elements are described bellow.

### 3.1 Seismic raptures and seismic(?) fault

Although the magnitude of the earthquake was important there was no clear surface rupture of the seismic fault, contrary to the earthquake of similar magnitude in Allah Bund region during 1819 (60-80 Km fault rapture and 6 to 9 m fault scarp). The longest rupture, with a total length more than 10 Km, trending to the E-W or to the ENE-WSW, observed almost 20 Km NNW from Bhachau, in the eastern prolongation of Kachchh Mainland Fault. The rapture, which is dipping $60^0$-$80^0$ to the south, is characterized by an en-echelon arrangement and accompanied by a morphological scarp more than 60–70 cm. The geometry and kinematics indicate a right lateral reverse movement.

No other rupture with such a big displacement detected so far, but many other smaller raptures of lesser importance observed. They were crossing through alluvial deposits or unconsolidated sediments as well the asphalt road from Bhachau to Bhuj and the adjacent villages.

Their length appear from few meters to several ten or even hundred of meters long whereas they have an E-W as well as an WNW-ESE direction. They have shown similar kinematic and dynamic characteristics to the major rupture that was described previously. The displacement was of few centimeters and rarely higher. The development of those fractures was very systematic in an en-echelon arrangement, forming two distinct zones. The first one and most important was developed parallel to the line Bhachau–Lakadla and follows the prolongation of the Katrol-Hill Fault zone whereas the second one locates more to the north in the adjacent area of the eastern prolongation of Kachchh Mainland Fault.

The kinematic and dynamic characteristics of all these raptures indicates that they could not be interpreted as liquefaction and lateral spreading phenomena [5]. As a result they could be regarded as the expression in the surface either the seismic fault or secondary tear fault or branch fault, located in the eastern prolongation of Kachchh Mainland Fault. The absence of any larger scale movement along the reactivated surfaces (something that could be expected regarding the order of magnitude of the earthquake and as happened with the earthquake of 1819) could be related to a flexural-type deformation and uplifting along the anticline structures of the Kachchh Mainland Fault major area.

### 3.2 Extensional raptures and open cracks

A grate number of systematic surface raptures with a different NW-SE trend observed in the major area. They also show a completely different kinematic and dynamic character and the most of them represent open or extensional cracks.

They are located mainly in the north of Bachau, in the adjacent areas of the eastern prolongation of Kachchh Mainland Fault and rarely southward in the prolongation of Katrol Hill Fault zone, along the Bhachau-Lakalda axis. Their size varies from 1-2 m to several ten of meters and they are developed systematically along distinct zones with a general E-W trend of direction. These fractures can be interpreted as the result of local extension due either to the right lateral movement along the reactivated surfaces, or to the flexural-type deformation.

### 3.3 Liquefaction phenomena

Liquefaction phenomena have extensively observed in many places in the epicetral area as well as in the adjacent region, like the area of Bhachau, Adhoi, Bhuj, Anjar, Mundra, Mandvi, in the port of Kandla but also in the gulf of Kachchh, in the Banni planes and in the Rann of Kachchh. All these phenomena was related to the local ground conditions (alliuvial deposits, lagoons, salt flats, estuaries etc.) as well as to the depth of water table.

In the surface these phenomena recognized as sand boils, lateral spreads, extensional failures and collapse features. A great number of surface ruptures that observed in the greater area is the result of liquefaction phenomena. Those ruptures however have different characteristics, relative to the others mentioned

Figure 2: Sand boils, extensional failures and open cracks.
5 Km to the north of Bhachau.

Figure 3: Small scale rock-falls in the road cut, 25 Km to
the east of Bhachau.

above, as they don't show relevant kinematic and dynamic features and their space distribution is neither systematic nor along distinct tectonic zones. Usually they are parallel to some morphological structures, such as shore lines, river beds, valley slopes etc. So on, their direction trend varies, as well as their size, which could be from a few centimeters to several ten of meters.

The surface water accumulation, which observed in many places after the earthquake (Bhuj-Bhachau greater area, Adhoi-Raper, port of Kandla, gulf of Kachchh, Banni planes, Rann of Kachchh etc.) seems to be related with these liquefaction phenomena and the water level changes, which is also a common phenomenon after or even before a seismic event.

### 3.4 Slope failures

The slope failures represented mainly by rock-falls phenomena and were observed in many places within the stricken area, mainly in the south of Kachchh Mainland Fault and in lesser extent in the region of Rapar and Rann of Kachchh. These phenomena have been detected in the areas where the morphological slopes, the lithology and the geometry of joints and other discontinuities of the rocks, generated the proper conditions.

The morphology of the region, which is the result of the active tectonics, is the principal factor provoking the rockfalls. These phenomena took place at the scarp of morphological discontinuities, which are mainly related with the faults of the area, at the slopes of the valleys which are crossing the area because of uplifting, but also at the road-cuts or on the anticlinal slopes.

## 4 Distribution of damages

The aim of this chapter is to correlate the tectonic structures and the geotechnical effects occurred during the earthquake with the great number of damages observed in buildings and infrastructures (ports, industrial facilities, manufacturing units, etc.) as well as in the lifelines (transportation, communications, electrical power and water supply).

The region where the maximum intensities recorded had a great extent (150x70 Km) and they are among the strongest ever reported in global scale and during recent events. The distribution of the intensities shows an elliptical development with the longitudinal axis in a general E-W direction [8]. The latter was parallel to the seismic fault indicating the important role of the E-W trending active faults in the distribution of the damages.

The maximum of intensities and damages was observed in the epicentral area and particularly on the hanging wall (Bhachau-Adhai greater area). This area was totally destroyed and as it is expected the most of the reactivated tectonic structures and geotechnical effects occured in this area.

As we could notice here while the damages distribution shows a regularity in relation with the distance from the epicentral area, there are isolated regions with strong intensities indicate serious damages due to numerous liquefaction phenomena such as sand boils, extensional failures and lateral spreading. The most typical example are the regions of Anjar and Kandla port where a great part

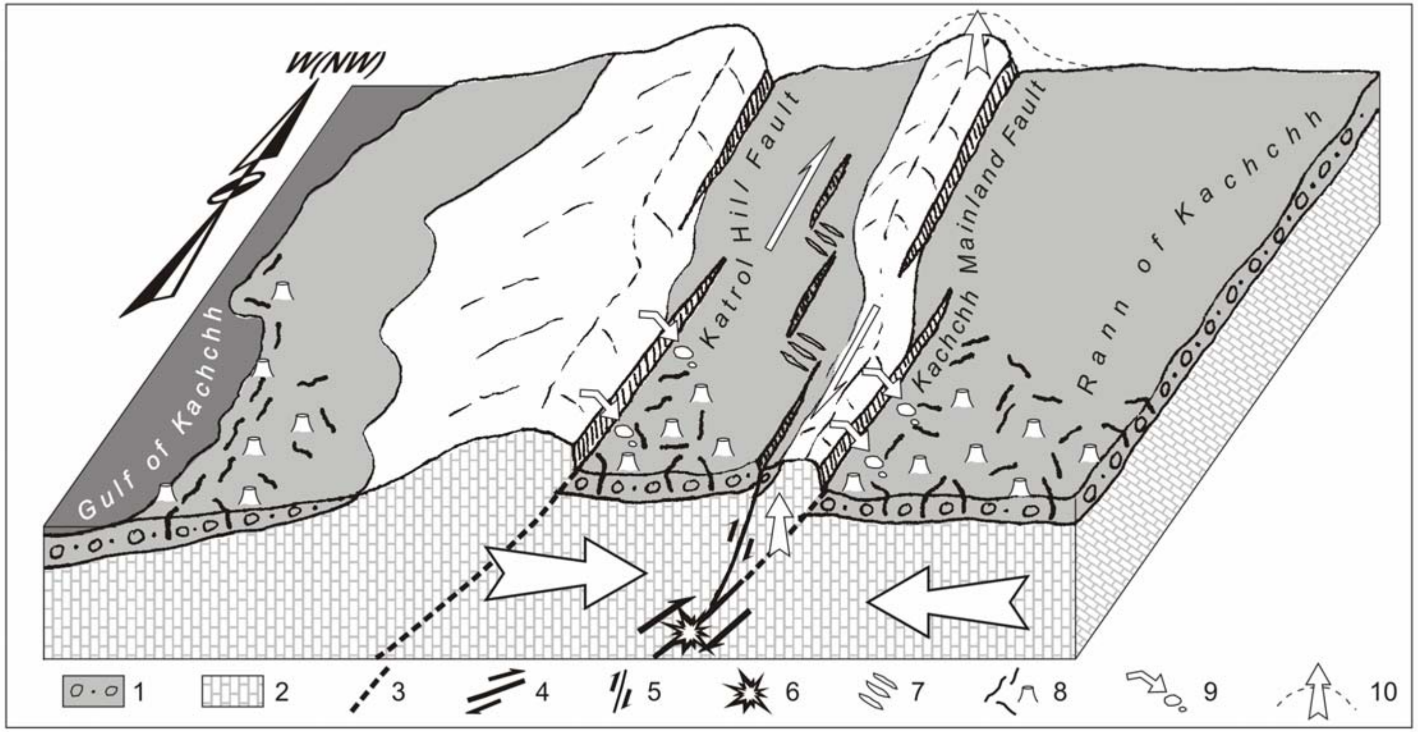


Figure. 4: Schematic block-diagramm representing the tectonic structures and geotechnical effects occurred during the earthquake. (1. Quaternary sediments, 2. Mainly phanerozoic folded sediments, 3. Non reactivated thrust faults, 4. Reactivated part of Katchchh Mainland Fault ?, 5. Reactivated secondary branch fault ?, 6. Earthquake source, 7. Open cracks, 8. Sand boils and lateral spreading, 9. Slope failures, 10. Flexural-slip folding.

of industrial infrastructures of the country and the portal facilities were destroyed.

From all the above described is obvious that except the parameters of the earthquake and the type of constructions, very important role in the distribution of damages have played the tectonic structures and the geotechnical effects occurring during the earthquake.

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