Bhuj earthquake of January 26, 2001: Effects in the Thar-Nagar Parkar region of Sindh, SE Pakistan

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ABSTRACT: *The Bhuj Earthquake of January 26, 2001 had devastating effects in India in terms of life and property loss. The epicenter being within 150 km from Pakistan's SE border, shocks were felt over a wide region in Pakistan, resulting in wide-spread damage to buildings and a life loss of around 15 people in the southeastern Sindh province of Pakistan. This paper presents results of a field visit to the Thar-Nagar Parkar region of SE Pakistan, outlining features related with liquefaction and ground failures as a consequence of the Bhuj Earthquake. These include sand blows in the inter-dunal depressions and lateral spreading at the crests and margins of the stable dunes. It has been noticed that a 170 km long belt of about 15 km width at the southern fringes of the Thar desert adjacent to the Great Rann of Kuchchh suffered widespread liquefaction, that resulted in damage to mud houses and cane huts in several villages, including the Tobo village (southeast of Diplo) where 25-30 such houses were completely or partially collapsed. No liquefaction was noticed at Nagar Parkar town (with bedrock as foundation) as well as in the northern parts of the Thar desert (probably due to low water table), and all the damage to buildings in this region was in response to ground shaking. Based on reported damage three isoseismal intensity zone have been identified 1) region encompassing parts of the Thar desert including towns/villages of Nagar Parkar, Islamakot, Diplo, Tobo, and Mithi is assigned an intensity of VIII on MMI scale based on extensive damage to masonry buildings and intensive liquefaction in parts of the region, 2) northern Thar desert, districts of Mirpur Khas, Badin and Hyderabad have been assigned intensity of VII, based on development of crakes and partial collapse to poorly constructed masonry buildings, and 3) region where buildings escaped damage but experienced swaying in response to ground shaking was assigned intensity VI, including the cities of Karachi and Sukkhar. Tectonic setting of the Thar desert and lower Indus basin underlain by Cretaceous normal faults and close proximity to two seismic zones, Kuchchh seismic zone in the southeast and Chaman seismic zone in the west-northwest, suggests that the region is susceptible to earthquake hazards. Further, the region is underlain by a thick cover of recent loose sediments, susceptible to liquefaction and with a capacity to amplify the ground shaking. Installation of a network of seismometers, strong-motion accelerographs and Global Positioning System (GPS) is essential to monitor seismic hazard potential of the region. Meantime immediate attention is needed towards public awareness about response to seismic hazards, reinforcement of buildings especially schools and development/implementation of building codes in the region.*

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INTRODUCTION

Earthquakes are no strangers to Pakistan. Located at and close to the active plate boundaries, there are virtually dozens of tremors every month in one or more parts of the country. Despite a virtually continuous seismicity, Pakistan has been lucky to experience only a few earthquakes of magnitudes greater than 7 on Richter scale, and the earthquakes leading to sizable life and property damage in Pakistan can be numbered on fingers. Quetta Earthquake of 1935 is considered to be the most devastating earthquake in the region now forming Pakistan, that resulted in life loss of > 60,000 (Ramanathan and Mukerji, 1938). Others include Pattan Earthquake (1974) and Darel Earthquake (1981) in North Pakistan. (Chandra, 1975; Jackson and Yielding, 1983).

The central and southeastern coastal region of Pakistan between Karachi and Nagar Parkar (Fig. 1) is generally believed to be tectonically stable. Yet, one of the greatest earthquakes in Indian subcontinent took place in the Rann of Kuchchh (immediately south of Pakistan border at Ali Bander) on June 16, 1819. After 182 years, the same region has been struck with another major earthquake on January 26, 2001, with epicenter near the town of Bhachau, District Gujarat, India. This has reconfirmed that the region is susceptible to seismic hazards in response to active tectonics.

This paper is based on field observations at Nagar Parkar and in the Thar desert in the month of June, 2001, some six months after the earthquake. Despite a considerable lapse of time, we noticed that scars of the Bhuj earthquake were still preserved depicting widespread liquefaction in the Thar and Nagar Parkar region of SE Sindh. A preliminary isoseismal intensity map based on damage to buildings and liquefaction is developed for SE Sindh.

REGIONAL GEOLOGICAL SETTING

The Thar region of SE Sindh marks the northern margin of the East-West oriented Great Rann of Kuchchh (Fig. 1). The geomorphic boundary between the Thar Desert in the north and the Rann in the south, more or less, marks the political border between Pakistan and India. The Kuchchh region is underlain by rift-like structures, which have been mapped offshore beneath the continental shelf with a general east-west trend (Biswas, 1987). On broader regional scale, the Kuchchh Graben is part of the Camby rift-system controlling the tectonic framework of Sindh-Gujarat region between Bombay in the SE and Karachi in the NW (Fig. 2). Besides the Kuchchh Graben, this region hosts rift-structures of Cambay Graben, Bombay Graben and Namada Graben. It is worth mentioning however, that the India-Asia collision ongoing since Eocene, has initiated a compressional stress regime in a northwesterly direction, which is very different from that at the time of rifting, and the normal faults associated with rifting are subject to inversion tectonics attaining reverse sense of displacement (Khattari, 1992; Chung and Gao, 1995).

The Thar-Kuchchh region is divisible into five major geomorphic zones (Malik et al., 2000), which include from north to south; 1) Thar Desert and the Nagar Parkar Uplift, 2) the Great Rann of Kuchchh, connected at its eastern end by the NE-SW oriented little Rann, both comprising saline wastelands, 3) Banni Plains, marked by raised mud flats, 4) Kuchchh mainland comprising rocky uplands, 5) coastal zone, marking the southern fringes of Kachchh mainland region against the Gulf of Kuchchh further to the south. The boundaries between these geomorphic zones are marked by faults of regional extent (Fig. 3).

The regional faults in the region include from north to south, Nagar Parkar Fault, Allah Band Fault and Kachchh Mainland Fault (Malik et al., 2000; Bilham, 1998).

Nagar Parkar Fault

The Nagar Parkar fault runs parallel and some 10-20 km north of the east-west geomorphic boundary between the Thar Desert and the Great Rann of Kuchchh. In the vicinity of the Nagar Parkar town, the

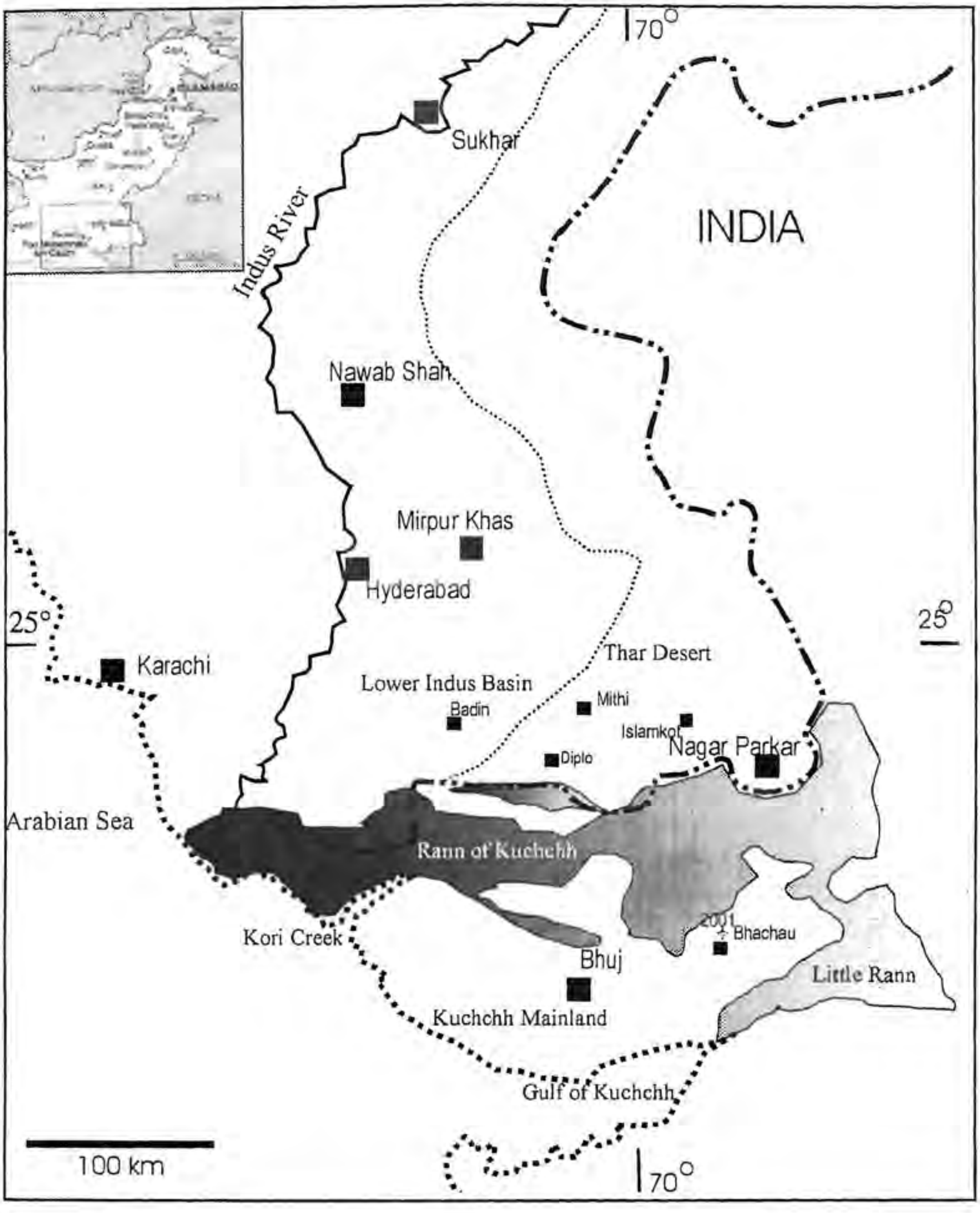

Fig. 1. Geographical sketch map of SE Sindh (Pakistan) and Gujarat province of India, showing location of the studied area of Thar-Nagar Parkar, separated from Kuchchh Mainland by Rann of Kuchchh. Epicentre of the Bhuj Earthquake January 2001 is shown for reference.

fault takes a northeastern turn and passes north of the Nagar Parkar Uplift comprising Karunjhar Hill and other hillocks exposing granites of the Precambrian Nagar Parkar Igneous Complex.

Allah Band Fault

A regional fault is considered to be running along the axis of the Great Rann of Kuchchh in an east west direction, some 10-20 km south of the India-Pakistan boundary (Malik, 2000). A major earthquake of magnitude 7.7 +-0.2 is associated with this fault epicentred at some 10 km north of the Fort Sindri (~10 km south of the current Pakistan-India border). The uplift associated with this 1819 earthquake created an 90 km long natural dam (later termed Allah Band) across the Kori creek-Puran distributary of the Indus River. The extension of the Allah Band fault to the west and the east is not so well defined. Malik (2000) consider it to run eastward along the axis of the Great Rann of Kuchchh, while Bilahm (1999) following account of Oldham (1926) proposes a northeasterly turn for the Allah Band fault some 50 km east of the Fort Sindry to follow the geomorphic boundary between the Thar desert and the Great Rann of Kuchchh. If so, it is possible that Allah Band and Nagar Parkar faults may join up north of the Nagar Parkar town, but there is no clear evidence for this.

Kuchchh Mainland and Associated Faults

The Great Rann of Kuchchh-Banni Plain, at their southern margin, abut against a series of low hills defining the Kuchchh rocky mainland, and the sharp contact, marked by an elevation contrast of about 120 meters between the two is defined by a regional fault termed Kuchchh Mainland Fault (Malik 2000). This fault is vertical to steeply inclined normal fault, that changes upwards into a high-angle reverse fault (Biswas, 1987). The southern wall of the fault defines a series of NW-SE to E-W oriented domes and antiforms which characterize the Kuchchh rocky mainland. Another regional fault termed Katrol Hill Fault passes through the central part of the rocky mainland which is itself associated by numerous folded hills similar to those along the Kachchh mainland fault. Up to 400 meter high Hill Ranges associated with these two regional faults traversing the rocky mainland are intervened by a Bhuj lowland (average altitude of 80-1000 m). The central and eastern parts of KMF have ruptured during the Bhuj Earthquake 2001 (Rastogi et al., 2001).

GEOLOGY AND STRUCTURE

The Thar desert occupies approximately 75,000 km^2 area in SE Pakistan. Much of the desert is covered by sand dunes. Kazmi (1984) distinguished three varieties of dunes, which included longitudinal, transverse, and Barchan type. Much of the southern part of the desert comprises stable longitudinal dunes, while the other varieties occur to the north in the transitional zones between the Thar, Thal and Cholistan deserts. The longitudinal dunes in much of the southern Thar desert are consistently trending NE-SW and some are as long as 10 km. Echelon geometry results in overlapping longitudinal dunes resulting in complex dunes some as long as 32 km (Kazmi and Jan, 1997). In terms of width, the longitudinal dunes are 200 to 250 meters wide with topographic relief of up to 100 m (Fasset, 1994). Small, narrow elongated depressions intervene the dunes and are covered by thin veneer of loamy soil. In the vicinity of the Great Ran of Kuchchh, such inter-dunal depressions are filled with playa type sediments and salt deposits. In this area these depressions commonly define saline lakes and marshes.

The subsurface geology of the Thar desert has only recently been come to be known in detail. Drill holes connected with exploration for coal have encountered (Rehman et al., 1993; Fasset and Durrani, 1994; Zaigham and Ahmed, 1996), from top to bottom, 1) 14-80 meters of sand from dunes, 2) 38-107 meters of iron-oxidized compact and

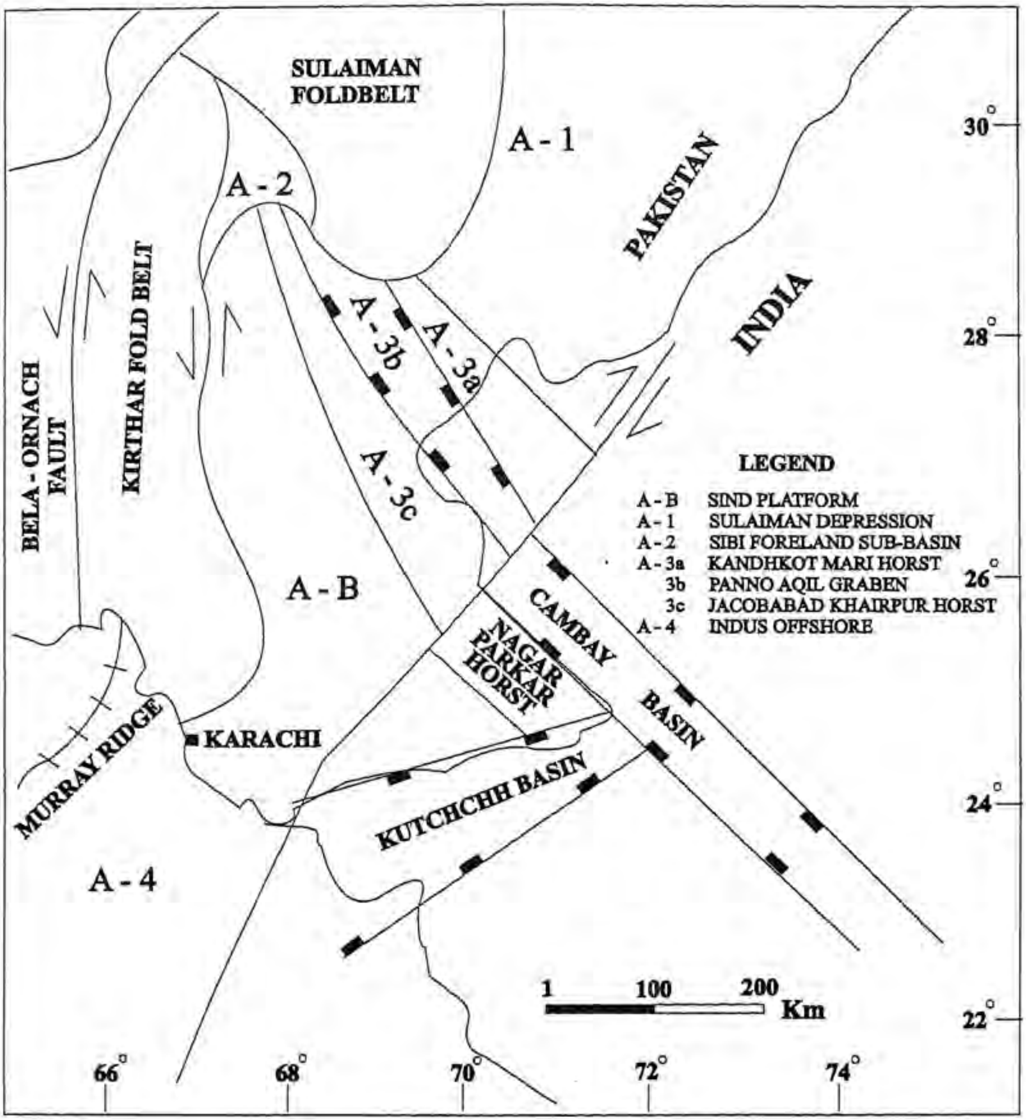

Fig. 2. Cambay rift province in SE Sindh and Kuchchh region (Modified after Biswas, 1982; Ahmed et al., 1994). Note that a limb of the Cambay Rift stretches across SE Sindh in a NW-SE direction including several horst-graben structures overlain by Cretaceous and younger sediments. Kuchchh basin is a WSW-ENE rift basin at right angle to Cambay Rift. Inversion tectonics of these normal faults in response to ongoing N-S compression is source of seismicity in the region.

incompact clay, slit and sand, 3) 0-185 meters of stratified rocks ranging in age from Jurassic to Eocene including up to 25 meter thick seams of lignite in the upper part, 4) granitic basement at depths of 112-279 meters. In an area of ~ 500 km^2 at the southeastern extremity of the desert, in the vicinity of the Nagar Parkar Town, this basement rock is exposed as a suite of Late Proterozoic A-type

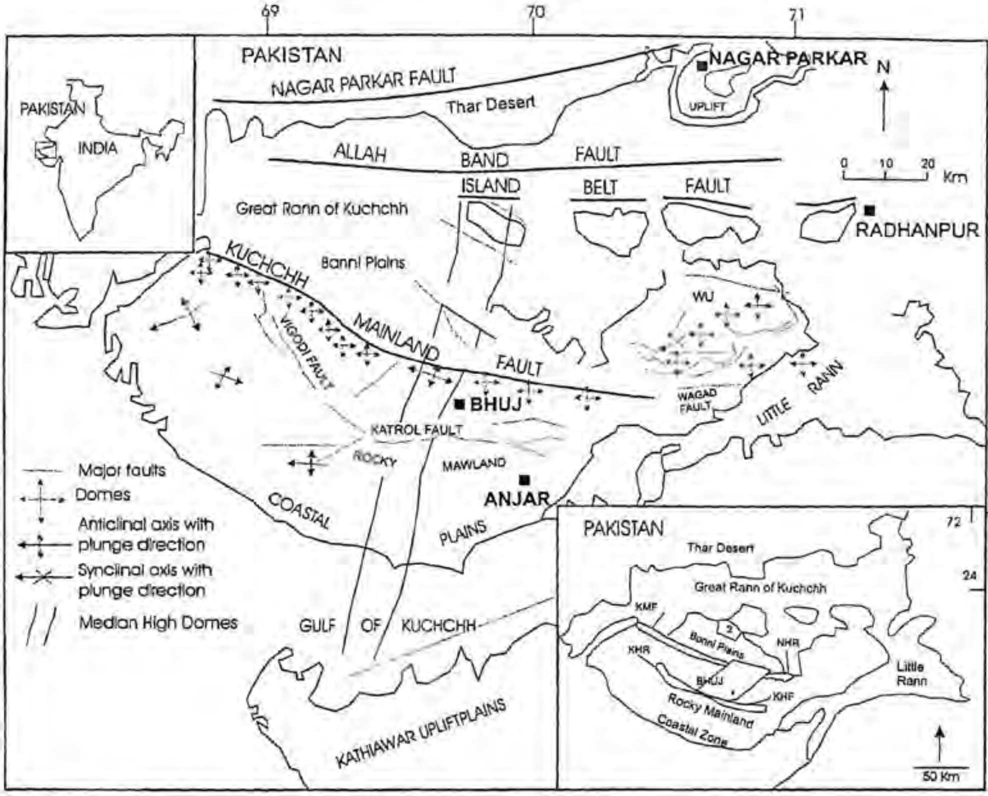

Fig. 3. Regional tectonic map of Kuchchh region showing major geomorphic zones separated by regional faults (Malik et al., 2000).

granites in the form of sporadic hills, intruded in a Proterozoic basement comprising amphibolites. This part of the Thar Desert represents a major uplift in the region, resulting in the absence of rocks younger than Late Proterozoic, probably due to erosion following the uplift. A buried fault with uplift of ~150 meters of this area relative to NW coal-bearing area marks the boundary of this uplifted area to the NW (Kazmi, 1984). Being a part of the western Indian shield, the Nagar Parkar granites and their host basement amphibolites belong to the post-Dehli tectonic/anaorogenic magmatic event dated around 850-750 Ma in the Aravali Craton (Roy, 1988). The Nagar Parkar Igneous Complex (Jan et al., 1997) resembles closely with granites from Siwana and Jalore in western Rajhstan, which yield Rb-Sr ages of 698 and 728 Ma.

Depth to the basement relative to the surface increases westward in the Thar desert. Whereas in the vicinity of Nagar Parkar village the basement is exposed at the surface, it gradually deepens to depths of 1500 m short of Mithi (Fig. 4). The depth to basement increases further west towards the current location of the Indus River, where it approaches to a depth of 3.5 km. A cross section across the Indus platform from the border area in the Thar desert to the Indus river (Fig. 5) depicts a west-facing pre-Paleocene half graben structure, with basement high underlying the Thar desert. A sedimentary wedge comprising sediments from Permian to Recent fills this graben structure, with base of the Palaeocene Upper Guru Formation defining a post-rift angular unconformity. Of particular interest to this study and liquefaction hazards in lower Indus Basin is the thick

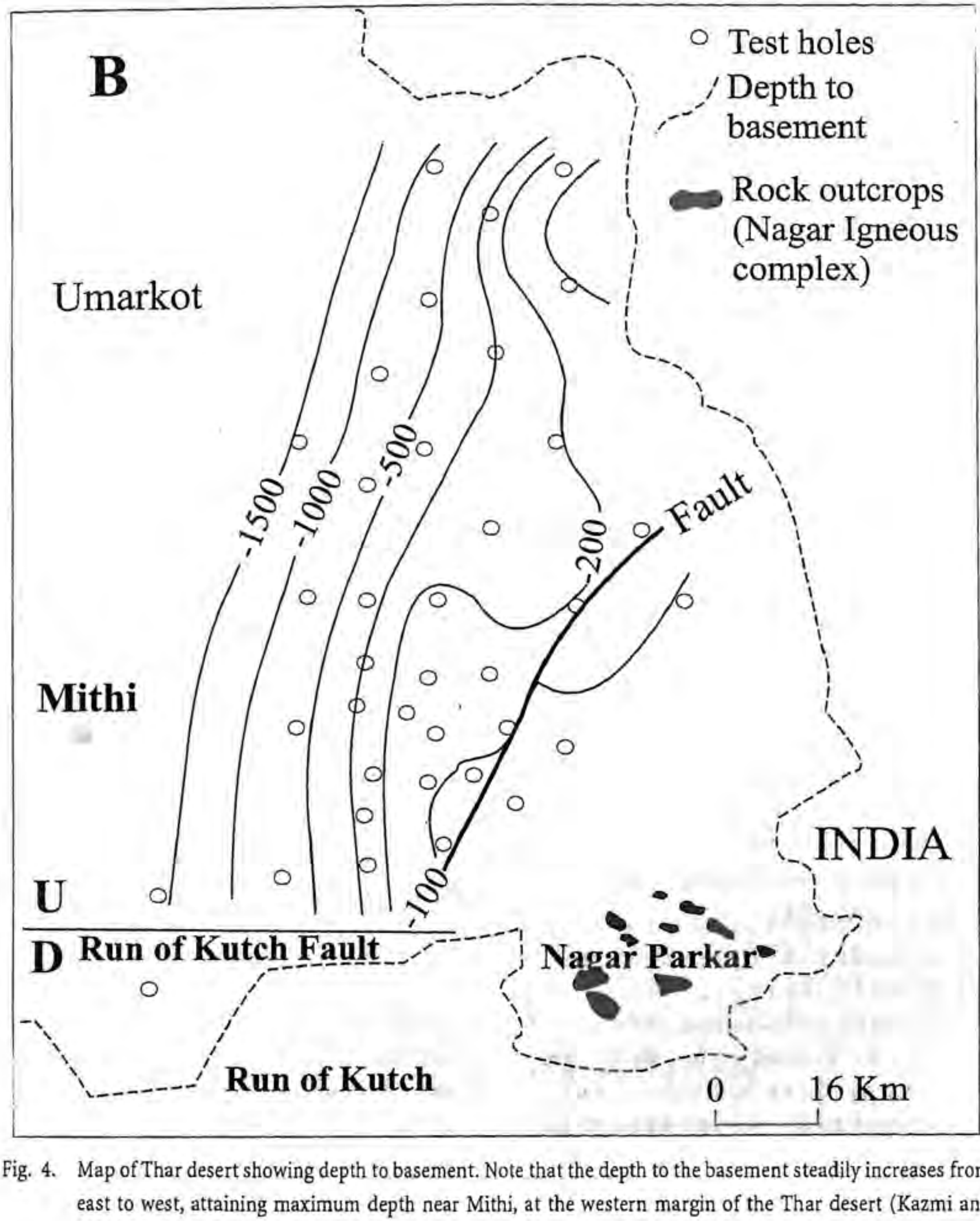

Fig. 4. Map of Thar desert showing depth to basement. Note that the depth to the basement steadily increases from east to west, attaining maximum depth near Mithi, at the western margin of the Thar desert (Kazmi and Jan, 1997).

quaternary deposits. It is noticeable that quaternary deposits in southern Sindh province (Fig. 6) are on average 200 meters thick with maximum thickness reaching 800 meters (Fig. 5). With high water table in the Indus basin, these recent sediments are highly susceptible to liquefaction in the wake of an earthquake of intensity of VIII or high.

The Thar desert and the lower Indus Basin, to its west, are covered by thick sand dunes and alluvium concealing the structure. The existing

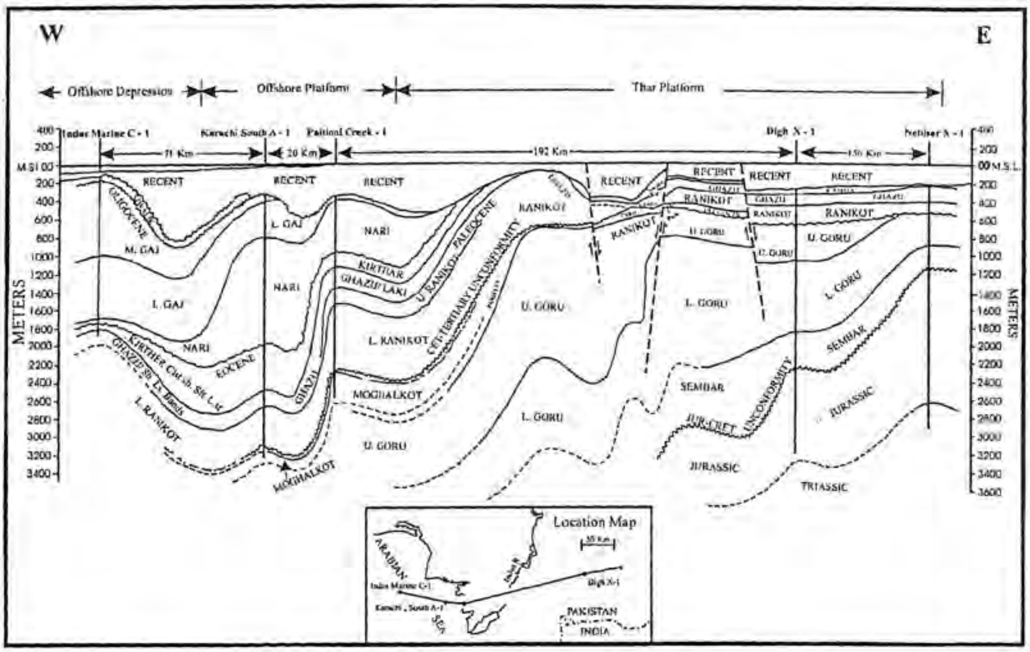

Fig. 5. Regional cross section across the lower Indus Basin from the Karachi depression to the Thar platform (After Kadri, 1994).

information regarding the structure of the region mainly comes from gravity, seismic reflection profiles and bore-hole data mainly related with petroleum and coal related exploration.

The lower Indus basin together with Thar desert in the east and Kuchchh region to the southeast is governed by faults associated with a Cretaceous phase of extensional tectonics in this region reflected in the Kuchchh-Cambay-Bombay rift systems. Whereas the Kuchchh region is marked by structures related with east-west oriented Kuchchh graben, the Thar and Lower Indus basin are controlled by NW-SE oriented extensional faults defining a series of grabens and horsts (Fig. 2). It may be noted that the Thar region together with the Gujarat District of India in the south is considered intra-cratonic in tectonic setting. In the context of ongoing Himalayan orogeny, the inherited extensional faults have potential to be reactivated. There have been suggestions that the western boundary of the Indian plate may be involved in collisional tectonics as east of the Bela-Muslim Bagh suture as Bhuj region of India (Stein et al., 2002).

MODERN AND HISTORIC SEISMICITY

Kachchh region experienced several earthquakes ranging from ML 4 to 8. Earthquakes with magnitudes 3 to 4 are however more common in this region. Based on historic record, Oldham (1883) and Chandra (1977) suggest subsidence and complete destruction of a town called Samaji (25 N, 68 E), located in the Indus Delta south of Hyderabad in May 1668. Amongst the large historic earthquakes, that of 1819 at Allaband is well documented (Bilham, 1999). Located approximately 70 km NW of the epicenter of 2001 Bhuj earthquake, the Allaband earthquake is assigned a magnitude of 7.7±0.2 (Johnston and Kanter, 1990; Bilham, 1999) and a maximum intensity of IX X+(MM) (Quittmer and Jacob, 1979). This is the largest earthquake to occur

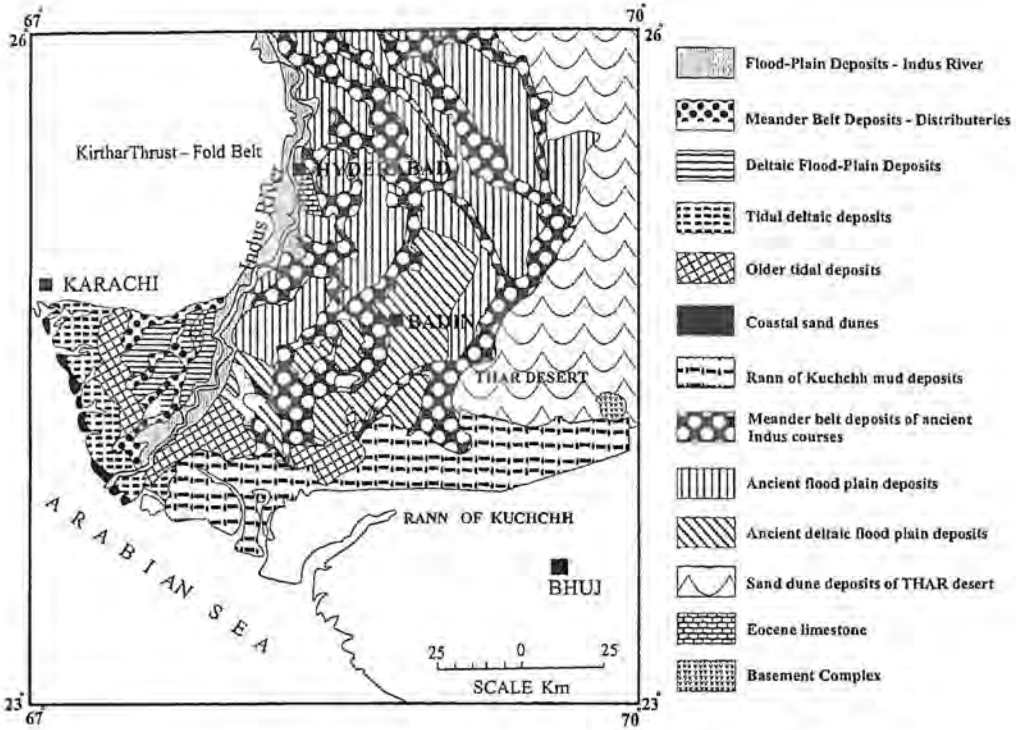

Fig. 6. Geological map of lower Indus basin showing Quaternary sediment deposits. With high water table in the Indus delta region, these mostly unconsolidated sediments are highly susceptible to liquefaction in the wake of an earthquake inducing intensities > VIII in the region (Kazmi, 1984).

in the Indian plate shield area and second largest in the world, after 1810-1811 New Madrid (USA) event) (Johnston and Kanter, 1990). Based on data recorded 6 and 25 years after the earthquake (references), Bilham (1999) inferred a coseismic reverse slip on a ~50° NE dipping fault in the shallow subsurface. Other important earthquakes in the region include 1945 Lakhpat earthquake that induced intensities up to VII, and Anjar Earthquake 1956 (Mw 6) that accounted for a life loss of > 100 people.

SURFACE DAMAGE

Since the epicenter of the Bhuj earthquake was about 150 km from the Nagar Parkar-Thar region, ruptures directly related with the movement of the fault responsible for the Bhuj Earthquake were neither expected nor found in the studied region. All the effects of the Bhuj Earthquake in SE Sindh province were, therefore related with ground acceleration, which can be categorized into two: 1) damage to buildings, 2) liquefaction.

Isoseismal Intensity

Ground shaking resulting from the Bhuj earthquake was felt in a widespread area in the Sindh province including the cities of Karachi (population > 12 millions), Hyderabad, Mirpur Khas, Nawab Shah and even as far to the north as Sukhar. Except for Hyderabad and Mirpur Khas, none of these major population centers suffered any loss to life or property and even the badly designed buildings either did not develop any cracks or did not get reported. Yet, people in all these cities noticed swaying of the

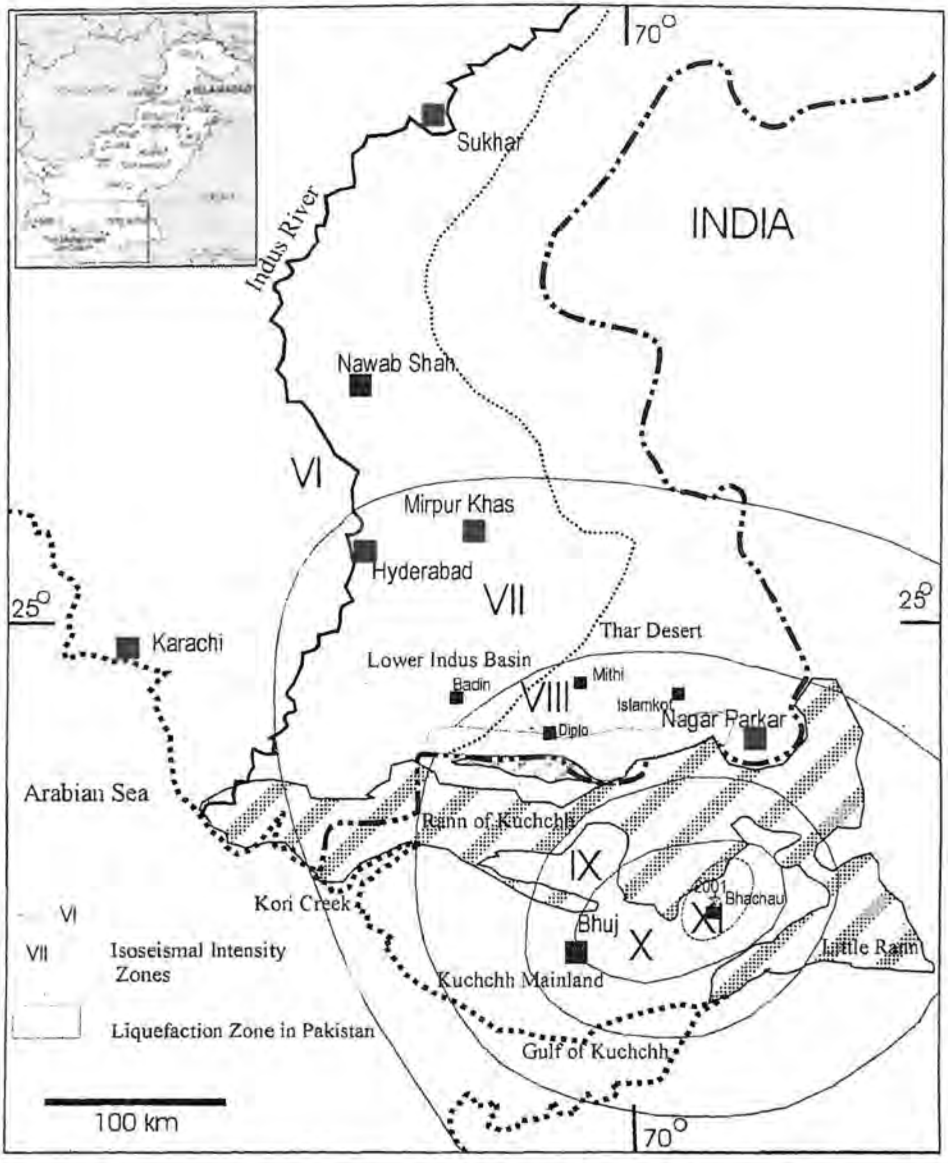

Fig. 7. Sketch map of the Sindh Province of Pakistan and Kuchchh region of NE India showing isoseismal intensity zonation related with Bhuj Earthquake 2001. Liquefaction was widespread in Rann of Kuchchh in India (Rastogi et al., 2001), however, since this study was focused to the north of the Indian border, only the region having suffered liquefaction in southern Thar desert is delineated. Isoseismal intensities in Gujarat province of India are taken from Rastogi et al. (2001).

buildings especially in the case of multistory buildings. According to Modified Mercalli Intensity (MMI) Scale, part of the Sindh province north and west of Hyderabad and Mirpur Khas (aerial distance > 300 km) and including the cities of Karachi and Nawab Shah can be assigned an intensity of V (Fig. 7). The cities of Hyderabad and Mirpurkhas, and including all the region to the south and southeast all the way to border with India (aerial distance of 150-300 km from the epicenter) can be classified as having suffered MMI level of VI and VII. Unconfirmed reports in the newspapers suggest 15 deaths and 70 people injured in this region. The Thar-Parkar district that borders India on the north side of the Rann of Kuchchh suffered heaviest damage to buildings. According to a government survey (Dawn, Feb 12, 2001) 674 houses have been fully damaged, and 3,357 have been partially damaged in Mithi, Diplo, Nagar Parkar, Islamkot and Chelher towns/villages. The Mirpur Khas district, that occurs to the north of the Nagar Parkar District suffered damage to buildings that was about 10 times less than the Thar Parkar district. This is evidenced by a report on damage to school buildings (Dawn, Feb 12, 2001). Whereas 964 schools were reported damaged in the Thar-Parkar district, 90 were damaged in the Mirpur Khas district. The city of Hyderabad, that occurs ~ 150 km north of border and 300 km from the epicenter, suffered noticeable ground shaking but only one poorly-built apartment building collapsed resulting in the death of two children. According to MMI scale, damage to poorly constructed buildings defines an intensity of VII that may be assigned to the districts of Mirpur Khas as well as to the district of Hyderabad. Unlike these two districts, the southern parts of the Thar Parkar district, including towns /villages of Mithi, Islamakot, Diplo, Nagar Parkar suffered heavy and widespread damage to poorly constructed buildings including partial collapse. This area additionally suffered widespread liquefaction. These criteria can be used to assign MMI level of VIII to this region. Figure (1) represents isoseismal intensity map of the SE province based on reported damage to buildings and liquefaction. The features related with liquefaction are further elaborated in the following section.

Liquefaction

One of the common consequences of earthquakes is liquefaction. Liquefaction may be defined as "the act or process transforming any substance into a liquid (Yeats et al., 1997). Strength and stiffness of a soil is lost due to ground shaking in response to an earthquake. Liquefaction typically occurs in saturated soils. Ground shaking causes the soils to collapse in response to increased pore pressure. A kind of hydraulic gradient induces upward flow of groundwater that includes a slurry of sand and water that erupts to surface as sand blows. Another common feature associated with liquefaction includes lateral spreading. A cohesionless soil when liquefied results in down slope transport of its overburden. This commonly results in extensional cracks. Yeats et al. (1997) estimate a depth of 10 meters for liquefaction, and a threshold of 0.1 g to produce liquefaction even in most susceptible sediments. They observe that liquefaction features are most common when the earthquake has a magni-tude > 5.

Liquefaction features were abundantly produced both in India as well as in Pakistan in response to the Bhuj earthquake 2001 (Rustogi et al., 2001). The Thar desert at its southern fringes is adjacent to the Rann of Kuchchh. The Rann is a wasteland of saline water with very high water table, as developed in response to a desertification of a former creek of the Indian ocean. Although the Rann of Kuchchh is oriented east-west as a distinct entity along the southern margin of the Thar desert, the two being separated by the Nagar Parkar fault, the low lands and depressions intervening the longitudinal dunes in the southern Thar desert are effectively part of the Rann and are marked with high water table and as saline wastelands. These depressions therefore define lobe-shaped tongues or tentacles projecting northwards from the main Rann. These depressions are filled with water in the rainy seasons in the summer but are dry with a thick salt crust in the winter. According to the eye-witness account, it was a rare phenomenon that these depressions became filled with water in the dry season of winter almost instantaneously as a consequence of the Bhuj Earthquake. The filling water obviously was not the rainwater rather was squeezed out of ground as a result of upward flow of the groundwater and eruption to the surface. Such depression intervening the longitudinal stable dunes preserved hundreds of sand blows at their marginal parts in June 2001 when this fieldwork was conducted. The biggest sand blow that was observed had a crater of over 3 meters lined by erupted sand and was as deep as two meters.

The response of the sand dunes was different from the inter-dunal depressions. Much of the south-eastern Thar desert is lined by stable dunes, in contrast to northern parts of the Thar desert where dunes are still active and have very loose cap of sand. The stable dunes have relatively stronger crust and have a good soil cover resulting in often thick vegetation cover. Whereas the fresh dunes in northern Thar desert, for instance near Islamakot and Mithi area either did not suffer any liquefaction (may be due to low water table) or if liquefaction did take place the fresh loose sand instantaneously filled out the cracks and depressions to hide the liquefaction effects. The stable dunes in the southern parts of the Thar desert in an east west oriented 20 km wide belt from Nagar Parkar in the east to Diplo (or even further west to Ali Bender) developed widespread lateral spreading in response to liquefaction. The lateral spreading in stable dunes was noticed to be in the form of extensional cracks and fractures with or without displacement. These cracks/fractures generally ran parallel to the axis of the longitudinal dunes and occupied the crest as well as the margins of the dunes. Where displacements were noted, marginal sides of the dunes almost always showed subsidence relative to the crests of the dunes. The maximum length of the cracks/fractures depended on the length of the dunes and at place was noted to be in excess of a km. The maximum widening or subsidence of one margin relative to the other did not exceed half a meter.

Whereas the principal damage to buildings in Nagar Parkar area and Thar desert owed to ground shaking, liquefaction played major role damage to houses in villages in the southern Thar desert. Since most of these villages are located on stable dunes, liquefaction-induced lateral spreading destroyed many mud houses as well as the huts made up of wooden sticks and canes. These types of houses when located in areas with bedrock as foundations (such as near Nagar Parkar) faired better than the stone/brick masonry buildings. Two villages SE of Diplo, named Toba and Bhakar Toba suffered typical damage due to lateral spreading at the crests of a dune. Twenty to thirty mud houses and cane huts in the each village collapsed due to dilatational cracks along the 50-meter wide crest of this stable dune. The interdunal depressions on the either side of this dune preserved some of the largest sand blows (diameter ~ 5 meters) observed in the region.

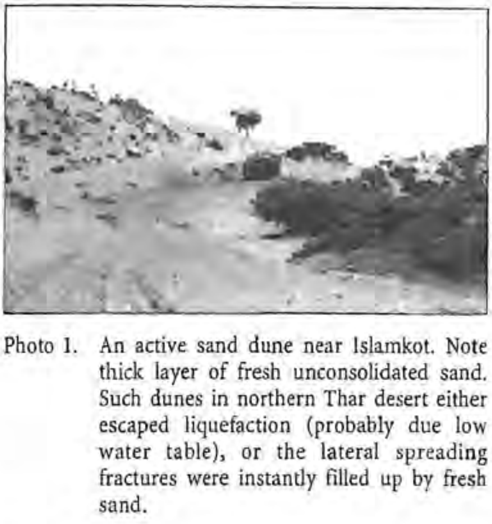

Photo 1. An active sand dune near Islamkot. Note thick layer of fresh unconsolidated sand. Such dunes in northern Thar desert either escaped liquefaction (probably due low water table), or the lateral spreading fractures were instantly filled up by fresh sand.

Photo 2. A typical stable dune in the southern Thar desert with lateral spreading fractures in response to liquefaction caused by the Bhuj earthquake. Note the inter-dunal depression filled with low water table. Such areas suffered intense liquefaction in the form of water fountains and sand blows.

Photo 3. A historical mosque near Nagar Parkar built in Mughal times suffered partial collapse in response to ground shaking.

Photo 4. Hindu temples near Nagar Parkar showing partial collapse in response to ground shaking.

Photo 5. A school building at Nagar Parkar developing extensive cracks in response to ground shaking. Such relatively modern governmental masonry buildings experienced more damage than privately owned older masonry buildings, due to poor quality building material and workmanship.

Photo 6. An historical Hindu temple near Nagar Parkar suffering partial collapse in response to ground shaking.

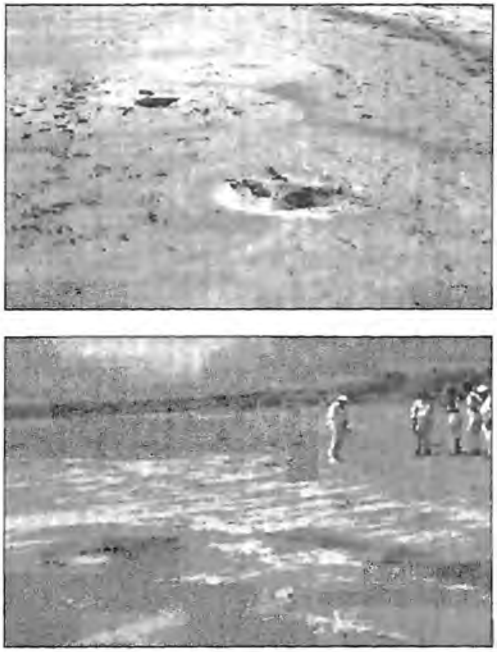

Photo 7-8. A series of sand blows at the margin of an inter-dunal lake.

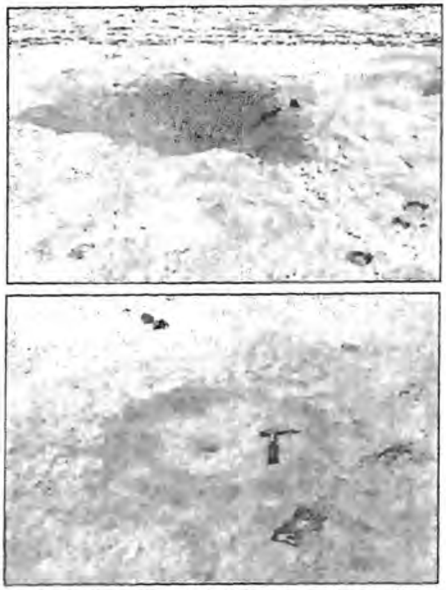

Photo 9-10. Close view of individual sand blow. This was the typical liquefaction feature in response to the Bhuj earthquake in much of the Rann of Kuchchh area and the southern Thar desert.

Photo 11. Margin of an interdunal lake adjacent to a stable dune. Note that the entire margin is lined up with a series of sand blows, while the dune suffered lateral spreading fractures parallel to the length of the dune.

Photo 12. Margin of a stable sand dune with fractures in response to lateral spreading liquefaction.

Photo 13, 14, 15. Close ups of Individual fractures. Note in one case the fractures traverse across the un-metalled road.

Photo 16, 17. Stable dunes showing a series of fractures related with lateral spreading liquefaction. Whereas in most cases such fractures were found parallel to the axis of the dune, but in rare case they traversed across the dunes.

Photo 18. A view of a village (Tobo) southwest of Diplo located at the crest of a stable dune. Some 20-30 mud and cane houses completely or partially collapsed in response to fractures related with the lateral spreading.

DISCUSSIONS

The Bhuj earthquake 2001 was one of the major earthquakes to occur in the vicinity of Pakistan in the recent past. The earthquake was felt all over the Sindh province, but damage occurred within a radius of 300 km from the epicenter (i.e., region falling within 150 km from the border at the Rann of Kuchchh). Widespread liquefaction reflected in sand blows and filling of inter-dunal depressions from upwelling groundwater together with lateral spreading in the stable dunes occurred in a belt of about 20 km width all along the southern margin of the Thar desert facing the Rann of Kuchchh from Nagar Parkar in the east to Ali Bander in the west. Mud and cane huts in several villages situated at dune crests partially collapsed with minor injuries to a few people. Since this area has only scarce population and masonry buildings are virtually non-extent, damage was far less than expected. The Nagar Parkar town and surrounding villages, where only a thin veneer of sand and soil covers the solid bedrock, liquefaction effect was almost negligible. All the damage to buildings in this area occurred to ground shaking. Even in this area, mud houses with light roofs made up of canes faired better than the masonry buildings. The old masonry building (stone in mortar) in the Nagar Parkar town did develop cracks but still faired better than the masonry buildings with concrete roofs built within last few years mostly by governmental departments (e.g., schools, dispensaries, rest houses), which suffered partial or complete collapse. This was due to poor quality of material being used in governmental buildings. A third area where masonry buildings suffered damage to the extent of partial collapse included the northern Thar Desert. Depth to bedrock in this area is as great as in the southern Thar Desert. This area has 1) low water table, 2) active dunes with thick cover of fresh unconsolidated sand. This area either did not suffer any liquefaction due to low water table or if the liquefaction did occur fresh sand instantly covered the resulting fractures. The damage to masonry buildings in this area was probably due to ground shaking.

Many news papers in their columns rightly termed the Bhuj Earthquake 2001, as a wake-up call for Sindh province especially the highly populated and congested cities of Karachi and Hyderabad. Already people have speculated that how did SE Sindh province escaped major damage even in response the Bhuj earthquake, when cities after cities were completely flattened in the Gujarat province of India. Hussain et al. (2002) speculated that probably the thick cover of soil on deeper-seated bedrock in Thar and lower Indus basin served as a cushion hampering the ground shaking. This is a complete misapprehension of the processes involved in propagation and amplification of the seismic waves. One of the basic concepts of the earthquake science is that poorly consolidated material such as the recent sediments covering the lower Indus basin and the thick sand dunes in the Thar Desert would amplify the ground shaking rather than hampering it (References). The primary reasons that SE Sindh province escaped substantial damage was due to its distance from the epicenter (> 150 km at any point). Secondly the region that was most susceptible to damage i.e., the southern Thar desert, is most scarcely populated. Thirdly, most of the houses in the Thar desert have low mud walls (or rarely stone in mud mortar) with very light roofs made up wooden sticks or canes. The nearest villages/towns with masonry buildings included Diplo (185 km Distance from the epicenter), Nagar Parkar (115 Km). These villages suffered considerable damage to buildings and even a partial collapse but time of the earthquake (9 am) was such that most people were out of their houses, that helped to have a minimum damage to life.

As far as the seismic hazard potential of the lower Indus basin and the Thar desert is concerned, a disaster at the scale of Bhuj earthquake is expected if a major earthquake with magnitude > 6 strikes the region with an epicenter located closer than that of the Bhuj earthquake. In terms of tectonics, the data from the Bhuj earthquake reveals that normal faults related with Cretaceous Cambay rift are subject to inversion tectonics. No surface scarp of the fault that caused the Bhuj earthquake is confirmed so far, although up to 2 km long zones of intense lateral spreading at N 23° 20' 30.4" E 70 11' 40.1" to N 23 20' 30" E 70 11' 53.9" could be manifestation of a subsurface scarp (Miranda, 2001). Aftershock seismity suggests that the fault plane responsible for the Bhuj earthquake oriented ENE-WSW with a dip of 45-50°. Existing fault plane solutions vary, but there is a general consensus that the Bhuj earthquake, in analogy with 1956 Anjar earthquake and 1819 earthquake of Allaband indicate reverse faulting (Rastogi et al., 2001). Since the Bhuj earthquake partially reactivated the Kuchchh Mainland Fault, that was a Cretaceous normal fault associated with Kuchchh graben, it appears that current N-S compression between the Indian plate and the Himalayas is causing inversion tectonics. As shown in Figure (2), SE Sindh province is underlain by a whole array of normal faults with intervening horsts and graben structures. This region intervenes between Kuchchh seismic zone in the south and Chaman seismic zone in the NW, which warrants special attention with regards to potential future seismic hazards faced by the Sindh province.

In case of a local reactivation of any of the Cretaceous normal faults underlying the lower Indus basin and the Thar desert, the thick cover of recent unconsolidated sediments in the region is most susceptible to liquefaction hazards. Additionally, these sediments are capable of amplifying the seismic waves far greater than the bedrocks. Figure (5) shows that recent sediments in the lower Indus basin attain thickness of up to 30 km. With a high water table, the entire lower Indus basin is susceptible to intense liquefaction. Sinking and complete collapse of the historical town of Samaji in 1668 (located to the south of Hyderabad) can be taken an example of the devastation liquefaction in lower Indus basin can cause.

Unfortunately, Pakistan is completely unprepared for seismic hazards. Firstly, the population is growing at alarming rates, which coupled with migration to cities is causing fast but uncontrolled growth of urban centers. Building codes are either inappropriate or non-existing. Implementation of the building codes is even worse. Public awareness of earthquake hazards is extremely poor and there is hardly any disaster management programme at public or governmental level. Above all there is a drastic lack of lack of scientific data about the potential seismic hazards in the country. There is an urgent need for installation of a network of seismic stations all over the country so that reliable seismicity data are collected locally. Likewise a network of oscillometres as well as a network of Global Position Systems need to be established so that not only instrumental intensities are regularly recorded but reliable data of neotectonic activity is available to the scientists for assessing true seismic hazards faced by different parts of the country. These studies are important in order to assess the potential seismic risk to over 30 million population in Sindh. Additionally large infrastructures such as the proposed Thermal Power Plánt at Islamkot using Thar coal deposits to generate electricity need proper assessment of seismic hazards before their structural designing.

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