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ABSTRACT

Intraplate earthquakes are ongoing activity in the Kachchh region. The area is seismically active and falls in Zone V of the seismic Zoning Map of India. The devastating Bhuj (Kachchh) Earthquake of MS 7.6 occurred in this zone on 26th January, 2001 causing severe damage to civil engineering structures and loss of human life. The surface manifestations of deformation of this earthquake include fractures/ fissures, lateral spread, slump, subsidence, upheaval, sand blows and craters. Bhuj Earthquake has caused considerable damage to earth dams lying in isoseist VIII and above in Kachchh. Damages to dams are in the form of longitudinal and transverse cracks, differential settlement, slumps/ slide, displacements and in some cases leakage.

A review of the available geological, seismological and geotechnical data have been done to asses the impact of Bhuj Earthquake and subsequent seismic events in the area on ground deformation and engineering structures. Main cause of the ground deformation and damage is liquefaction of the soil under seismic shaking. Tectonic influence on the development of fissures/ cracks on the ground as well as on the earth dams has been observed.

INTRODUCTION

Bhuj Earthquake caused unprecedented devastation in the recorded seismic history of India. Almost every man-made facility, suffered severely in Kachchh district. A total of about 1.3 million houses, besides numerous earth dams, roads, bridges, railway lines, ports, hospitals, electricity lines, water pipes, telephones, etc., were damaged depending on their distances from the epicenter, ground condition and type of construction. Heavy damages to buildings have been observed as far as 250 km away from the epicenter. Bhuj Earthquake is one of the best studied intra-continental earthquakes in the world by the national and international institutes, organizations and individuals. Attempt has been made to review and synthesize available geological, seismological and geotechnical data related with the ground deformation and damages to structures especially earth dams.

PHYSIOGRAPHY

Kachchh (Kutch) is a district of Gujarat state in western India covering an area of 45,612 km² surrounded by the Gulf of Kachchh and the Arabian Sea in south and west, and by the Great and Small Rann in the northern and eastern parts. This region can be divided into four physiographic units namely, Rann (salt marsh), Banni Plains (grass land), Hilly tracts or highlands and Coastal plains or low lands. The Rann is dissected by a few sandy and rocky mounds giving appearance of islands. The hilly tract comprises the island belt (Pachham, Khadir, Bela and Chorar) in the north, Wagad region in the northeast and the Kachchh Main Land in the central part. Landscape of Kachchh region is mostly structurally controlled.

Katrol hill range, in the mainland, is the highest area forming E-W water divide for north and south flowing rivers. Rivers in the area are short and ephemeral. Catchment area of the rivers is small. These rivers are flowing radially following hump shaped topography of the region. Consistent flow of water is rarely observed in the rivers even during the monsoon period reflecting the present hyper-arid climate necessitating construction of many small and minor dams for the water storage.

GEOLOGY AND STRUCTURE

The rocks exposed in the Kachchh are of Mesozoic, Tertiary and Quaternary age (Fig. 1 & 3). Gently folded Jurassic, Cretaceous and Tertiary rocks form highlands and Quaternary sediments low lands. Mesozoic sediments (sandstone, shale, marl and limestone) constitute the major part of the basin deposit. The Tertiary sediments (sandstone, conglomerate, clay, marl, siltstone and limestone) border Mesozoic uplift area in the peripheral and intervening structural lows. The

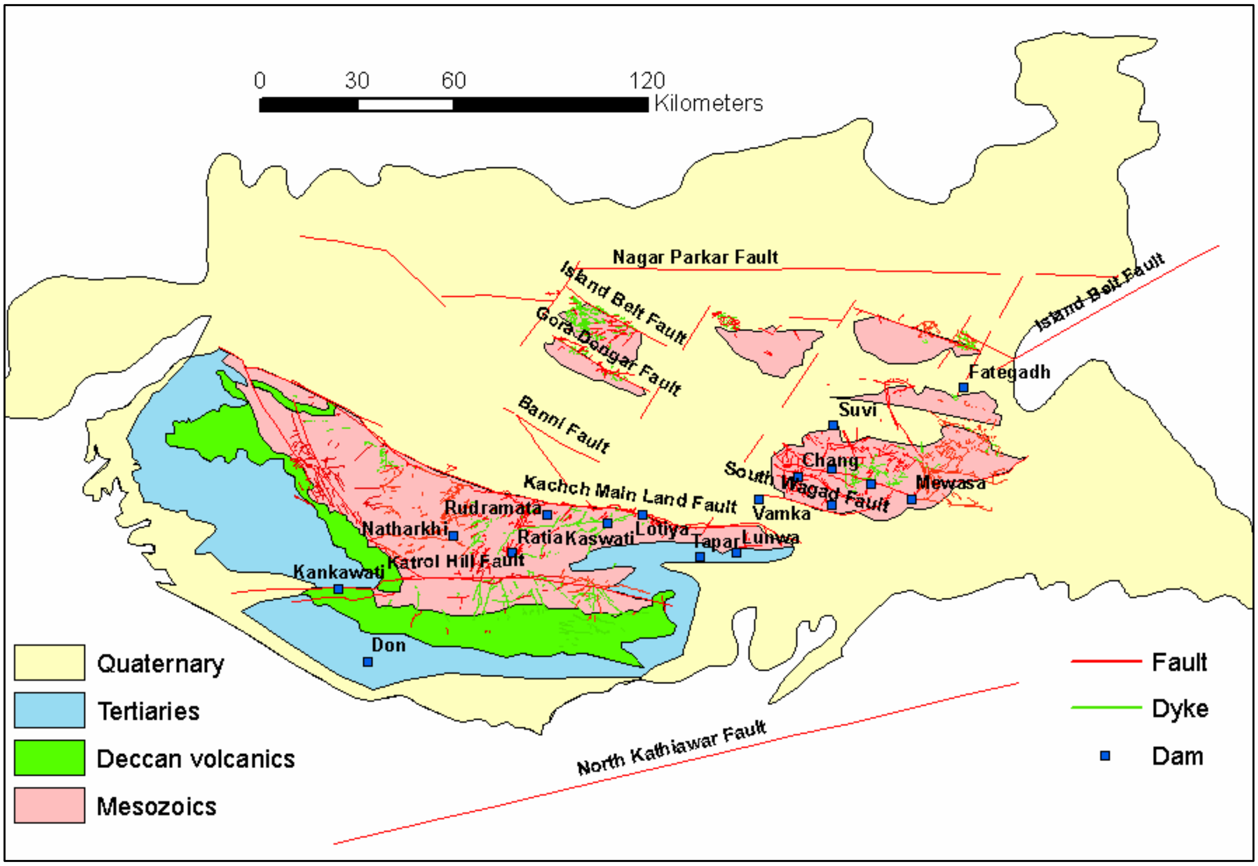

Fig. 1. Generalized geological Map of Kachchh showing locations of damaged earth dams (modified after Biswas and Kahatri 2002 and GSI 2003)

Mesozoic-Tertiary sequence is intervened by the Deccan basalt flows and associated intrusives of Cretaceous-Eocene age (Biswas, 2005).

The Kachchh region is an intra plate pericratonic rift basin (length 320 km, width 160 km) oriented in E-W direction. The basin structure styled is controlled by E-W longitudinal master faults namely Katrol Hill Fault (KHF), Kachchh Mainland Fault (KMF), South Wagad Fault (SWF), Gedi Fault (GF) and Island Belt Fault (IBF) (Fig. 2 and 3). Bouger gravity anomaly in the area is high and aligned in E-W direction (GSI, 2003). The foot wall uplifts (structural high) along master faults formed the highlands and intervening half-grabens formed the plain lands (structural lows).

The Nagar Parkar (NP) Precambrian block and Saurashtra block are respectively the northern and southern rift shoulders. The Radhanpur arch trending NNW-SSE is the hinterland high, which limits the rift extension to the east. To the west, the rift is open merging with the continental shelf. The slope of the basin is toward southwest. A meridian high (hinge zone) aligned in NNE-SSW direction traverses middle of the basin resulting in bilateral plunge of the uplifts. Eastern part of the basin is shallow relative to western part. Most of the uplifts occur in the eastern part of the basin indicating more tectonic activity in this part (Biswas, 2005).

TECTONIC FRAMEWORK

The tectonic set up of the region is governed by three major Precambrian geofractures NE-SW Aravalli-Delhi trend, ENE-WSW Son-Narmada-Tapti (SONATA) trend and NNW-SSE Dharwar trend. The Kachchh Rift Basin (KRB) is the earliest pericratonic rift basin formed in the western margin of the Indian craton during the Late Triassic break up the Gondwanaland along Precambrian structural trends. The rifting process ended up with the change of stress direction due to rotation of Indian plate during Late Cretaceous pre-collision stage. At this time most of the uplifts came into existence by up thrust of the footwall blocks. The KRB developed in an extensional stress field but changed to compression due to inversion of tectonics after the Miocene. Himalayas exerted a back push due to continuing movement of the Indian plate towards north causing stress in opposite direction resulting in strain condition in Peninsular mass. Drifting of Indian Plate induced horizontal stress in the area resulting in the change of normal faults into wrench faults.

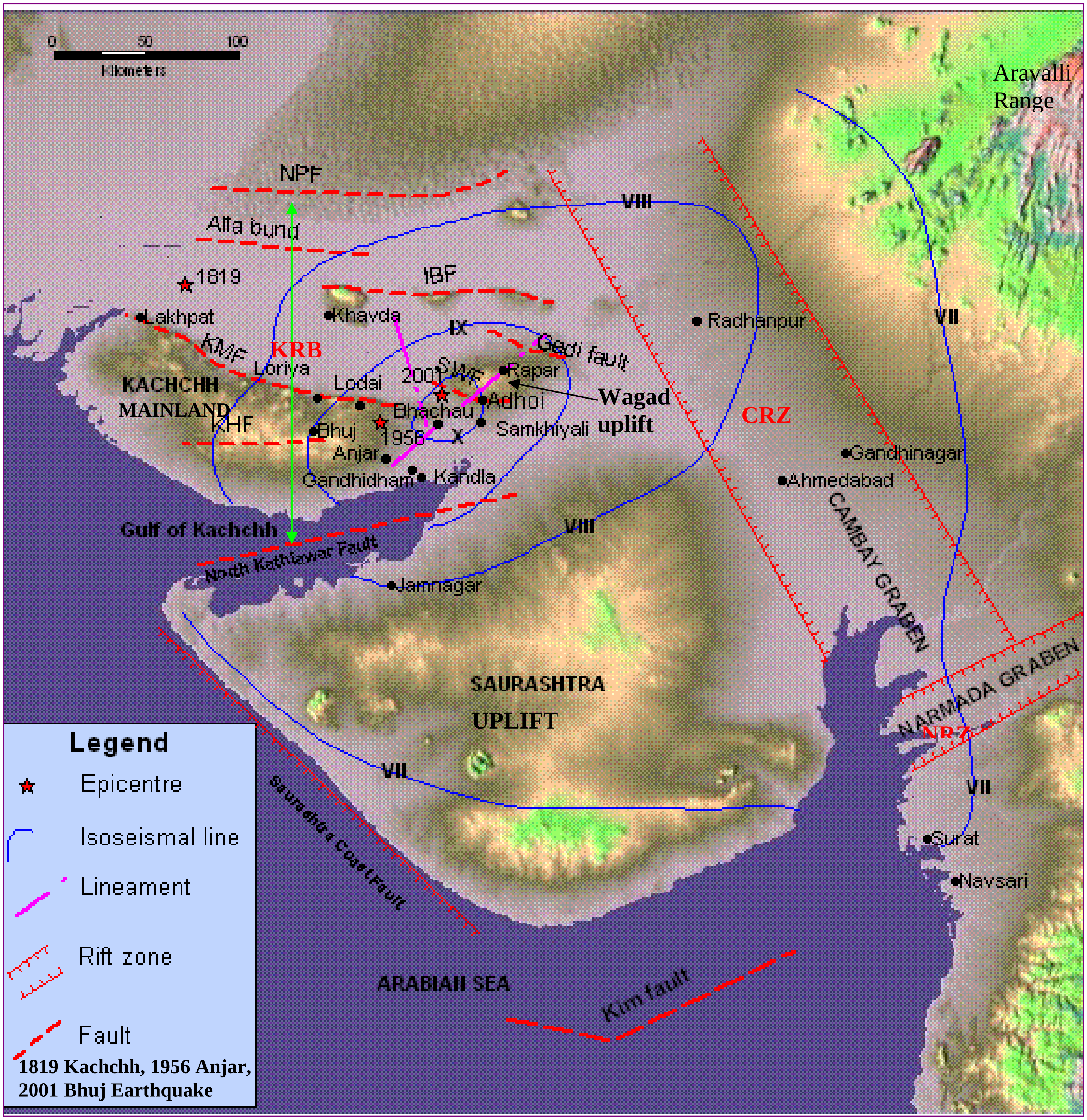

Fig.2.Physiography and seismotectonic map of Gujarat (modified after Biswas and Khatri 2002 and GSI 2003)

Three major faults occur within the rift, which follow the curvilinear trend of Delhi fold belt. Uplifts along these sub-parallel master faults produced intra-rift horst-graben and half graben structures in linear arrangements that controlled the sedimentation and structuring. All the structural lows between the uplifts merge into a vast plain land dotted with highlands forming characteristic geomorphology of Kachchh. The present structural style of KRB evolved by lateral slip of the faults causing shifting of the uplifts progressively eastward, relative to each other from south to north. The strike-slip related structuring modified the linear flexures breaking them into individual folds. Narrow deformation zones were formed along the master faults (Biswas, 2005). Faults and dykes in the area are generally aligned in E-W, NW-SE and NE-SW direction (Fig. 1).

SEISMICITY AND SEISMOTECTONICS

Intraplate earthquakes are ongoing activity in the Kachchh region. The area is seismically active and falls in Zone V of the Seismic Zoning Map of India (IS1893, 2002). A number of earthquakes of magnitude ranging from < 4 to 7.8 have occurred in this region. The major seismic events of Kachchh region include 1819 Kachchh (Mw 7.8), 1956 Anjar (Ms 6.1) and January 2001 Bhuj (Ms 7.6) earthquakes (Fig. 2). Earthquakes of magnitude < 5.6 are still continuing in the area.

Gaur (2001) has explained the intraplate earthquake of Killari (1993), Jabalpur (1997) and Bhuj (2001) as a consequence of stress transfer southward of the Himalayan compression zone. The movement of the Indian Plate towards north has resulted in the formation of deep seated lineaments (Mehta and Prakash, 1982). Bilham (2001) holds the view that the Himalaya depresses the leading edge of India causing thereby bending of the Indian plate and significant earthquakes within the Indian Subcontinent occur south of the flexural bulge 600 to 1,500 km south of the Himalaya, where plate stresses rise above ambient stress levels. Rajendran et al. (1998) inferred that regional stress in the Kachchh area is in the NW-SE direction, RaviShankar (1995) suggested that the differential and crustal structures provide the first order motive force for relative movement between various crustal blocks under the NNE-SSW compressional stress due to northward movement of the Inidan plate. This stress is accumulated at the fault intersections or at the fault joints to generate the intra-plate earthquakes. Schweig et al. (2003) have compared Kachchh and New Madrid regions having rift type geotectonic setting and observed that in both regions attenuation of seismic waves are low. Contrary to other views, they concluded that earthquakes relax high ambient stresses that are locally concentrated by rheologic heterogeneities, rather than loading by plate-tectonic forces.

Kayal et al. (2002) inferred that deep-seated hidden fault at the base of the Kachchh palaeo-rift zone are activated by reverse faulting due to compressional stress. The main 2001 Bhuj Earthquake shock generated the aftershocks at deeper as well as at shallower depth by shear adjustment and fault interactions. The main Bhuj Earthquake shock is located north of KMF. Inferred blind causative fault trend is in ENE-WSW direction. On the basis of surface faulting and

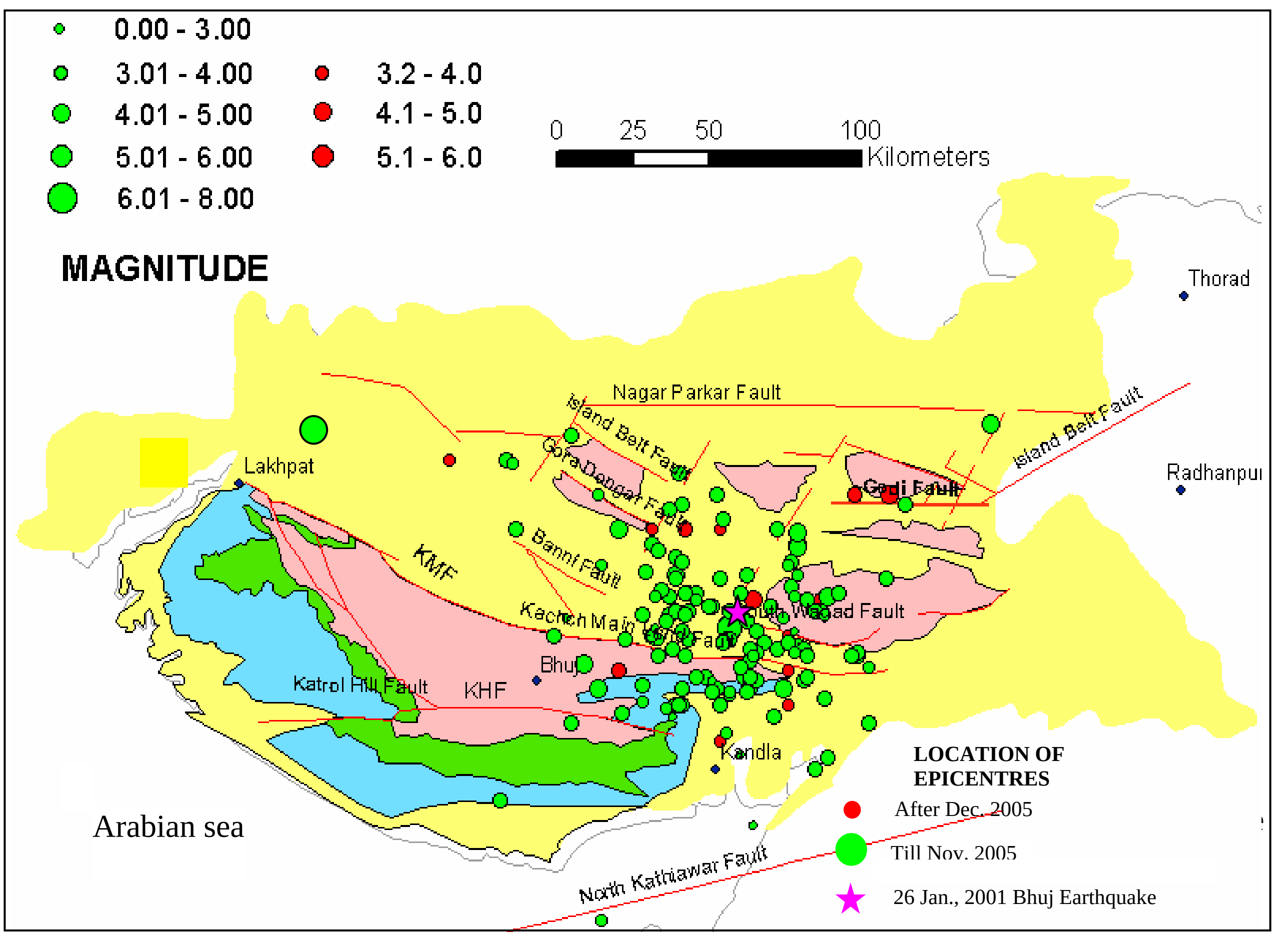

Fig 3. Location of earthquake epicenters on geological map of Kachchh (EQ data source: USGS and IMD)

neotectonic evidences, McCalpin and Thakkar (2003) interpreted that 2001 Bhuj Earthquake main shock plane developed parallel to KMF at a distance 30 km northward, dipping southward, is not totally blind thrust.

KMF is overstepped by SWF in the eastern part of the basin forming over step convergent transfer zone which is undergoing transpressional stress in the strained eastern part of the basin. This is a site for rupture nucleation as evident from epicenters of 1956 Anjar (Ms 6.1) and 2001 Bhuj (Ms 7.6) earthquakes and subsequent recent earthquakes (Biswas, 2005). Since 1819 earthquake, seismic events in the area are shifting towards east and north east between Kachchh Main Land Fault and Gedi Fault as indicated by the concentration of aftershock epicenters in this part of the basin (Fig. 3).

ISOSEIST CHARACTERISTICS OF BHUJ EARTHQUAKE

Geological Survey of India has carried out detailed isoseismal survey of Bhuj Earthquake. The shocks were felt as far as 1800 km away from the source area. The long/ short axes ratios of isoseismal X, IX, VIII, and VII are 1.36, 1.59, 0.95 and 1.14, respectively. These erratic ratios are indicative of tectonic control in the distribution of radiated seismic energy (GSI, 2003).The shape of the isoseismal is elongated towards NNE indicating influence of transverse Anjar-Rapar lineament roughly parallel to Aravalli trend (Fig. 3). Shape of the isoseismals indicates that the intensity attenuates in the southwestern and accentuates in the northeastern quadrants. The Isoseist VII swerve and follows an almost N-S trend in Mainland Gujarat indicating the strong influence of Cambay graben in the distribution of seismic energy (Fig. 2).

NATURE OF SOIL, LIQUEFACTION AND GROUND DEFORMATION

Soil liquefaction is the sudden, near total loss of shear strength as a result of excess pore water pressure. Most important factors governing the liquefaction process for in situ soil are intensity of earthquake and its duration, location of ground water table, soil type, relative density, particle size gradation, particle shape, weathering, drainage conditions, confining pressures, cementation of the soil deposit and additional loads of engineering structure on these deposits. The vibration from earthquake causes sand grains to shake into a smaller volume. If the excess pore water does not have time to drain out, soil will be in a liquid state. Liquefaction during earthquake shaking is generally confined up to 10m depth. The susceptibility to liquefaction is greatest in the case of uniform fine sand (Lambe, 1969). Soil in Kachchh area is mainly loose sand and silt with little or no fine sediments and thus susceptible to liquefaction under strong ground motion, wherever ground water occurs at shallow depth.

McCalpin (1996) suggested that high shaking threshold 0.1g (PGA) is required to develop liquefaction features and magnitude of about 5.5 to 6 is the lower limit for liquefaction effects. Bhuj Earthquake was of magnitude (Ms) 7.6. Severity of Liquefaction in the areas of intensities X and IX was very high to high, moderate (widespread) in intensity VIII, Low (subdued) in intensity VII and Very Low (stray) in intensity VI. Thus threshold value for initiation of liquefaction for Bhuj Earthquake was VI (GSI 2003).

Ground deformations in the form of sand blows/ sand-boils, ground fissures, ground subsidence, mud craters, subsidence craters, sand dykes, lateral spreads, slumps, raised ground and minor slides were observed in the Rann of Kachchh, Banni and Little Rann covered by Holocene sediments (Fig. 4). These features are the manifestations of liquefaction on the ground due to strong Bhuj Earthquake shaking. Sediments in the above areas consist mostly of loose, non cohesive, fine sand-silt fractions and groundwater table generally occur at shallow depth (<10m). Ground fissures especially within isoseismal IX and X are aligned in E-W, ENE-WSW and WNW-ESE direction. Prominent localities where coseismic deformations such as ripping of surfacial rock mass and fissures were observed include Bodhomora (upheaval site), Sikra (Rupture zone), Kakarwa (fissure), Vondh (Rupture zone) and Chobari-Manfara-Kharo (Rupture zone). Fissures in the Mesozoic sandstone covered with thin soil were also observed at places, as a consequence of Bhuj Earthquake, in the Meizoseismal area.

A series of spouts aligned in ENE-WSW direction were observed about a metre above the water surface in the reservoir of the Kankavati Dam located about 120 km WSW from the epicenter of the Bhuj Earthquake. Water in the reservoir started disappearing in the ground immediately after the earthquake. In the reservoir bed small craters in a line extending up to a distance of 100 m from the upstream toe of the earth dam were observed in the continuity of ground fissures developed, indicating structural control of deformation during Bhuj Earthquake.

POST EARTHQUAKE STUDIES

A number of organizations like Geological Survey of India (GSI), National Geophysical Research Institute (NGRI) and Indian Seismological Research Institute (ISR) are carrying out earthquake related studies in Kachchh area. These studies include geophysical surveys, crustal deformation and Global Positioning System (GPS) measurements, site response studies, attenuation studies and Ground Penetrating Radar (GPR) survey and microzonations of vulnerable areas of Gujarat (Rastogi et al., 2007). Bhuj town has been divided in three zones (good, fair and poor foundation grade) based on the hammer seismic survey and ‘N” values. Two layers with interface depth varying from 4.0m to 17.5m have been identified (Rastogi 2007). The velocity of P-wave is 833 to 1579 m/sec in upper layer and 1538 to 3793 m/ sec in the lower layer. Based on structural response recorders and weak motion recorders for 2001 Bhuj Earthquake PGA exceeding 0.6g has been estimated very near epicenter and 0.31-0.37 g at Bhuj (Iyengar and Kant, 2005). NGRI has estimated site

Fig. 4. Co-seismic ground deformation in Kachchh

response in the Kachchh Mainland and Wagad uplift areas based on H/V spectral ratio. The mean amplification factor obtained for soft sediment (Quaternary/ Tertiary) sites varies from 0.75-6.03 times for 1-3 Hz and 0.49-3.27 times for 3-10 Hz. The mean amplification factors obtained for hard sediment (Jurassic/ Mesozoic) sites range from 0.32-3.24 times for 1-3 Hz and 0.37-2.18 times for 3-10 Hz. Amplification factor 1-2 has been obtained at sites by ISR (Rastogi et al., 2007). Centre for Mathematical Modelling and Computer Simulation (C-MMACS) and GSI obtained site amplification of 2-5 for frequency 0.4-0.8 Hz (Parvez and Madhukar, 2006). Results of other field studies when available will help in refining seismological and seismotectonic estimated and interpreted data.

PEAK GROUND ACCELERATION

The Bhuj Earthquake ground motion brought unprecedented devastation and destruction to the man made structures in Gujarat. The earthquake produced very strong ground particle motion in the epicentral tract for nearly 60 seconds. At the time of occurrence of 2001 Main Bhuj shock only one strong motion accelerogram was located in Ahmedabad (at 230 km distance from the source) which recorded Peak Ground Horizontal Acceleration 0.1g. The Peak Ground Acceleration (PGA) as recorded by the Structural Response Recorders (SRR) located at different places in Gujarat varied from 0.25g to 0.55g; the maximum 0.55g was recorded at Anjar. Individual higher PGA values of 0.33g, 0.38g, 0.14g and 0.13g were recorded at Kandla, Niruna, Porbandar and Ahmedabad, respectively (GSI, 2003). Iyengar and Kant (2005) have estimated PGA by analytical methods near Bachau > 0.6g and at Bhuj 0.31-0.37g. The maximum estimated acceleration from damages of structures near source is 0.7g (Krinitzsky and Hynes, 2002 and Rastogi, 2001).

DAMAGE TO ENGINEERING STRUCTURES

In the Kachchh area Type-A, B and C buildings suffered nearly total damage of Grade 5 in the epicentral area and at distance damage was restricted to Grades 1 to 3. Walls of the type-A and B structures failed under the influence of strong motions. Traditional design of light roof helped in saving many lives in Type-A structure whereas concrete slabs as a roof of the type-B structures became principal cause of the causalities which caved in on failure of load bearing walls. Reinforced Concrete (RCC) columns of type-C structures were sheared from the base causing super structure to collapse. Ground floors kept open for parking in many buildings without properly designed coloumns and tie beams were found crushed. Buildings located about 250 km away up to Ahmedabad have collapsed and suffered severe damage. The multistoried buildings with parking space and buildings with additional constructed floating structures on upper floors suffered maximum damage. GSI obtained amplification of 2-5 and identified low velocity areas within the Ahmedabad city but locations of damaged multistory buildings do not coincide with the zones of low velocity and high amplification. Fundamental frequency of 0.6 Hz of 300-350 m thick alluvial soil has been obtained at Ahmedabad i.e. matching with the frequency of 20 stories buildings. Amplification of 1-2 for frequencies 8-10 Hz for surface layer at Anjar has been obtained (Rastogi, 2007).

Roads and bridges falling in isoseismal zones IX and X were damaged involving development of cracks, slope failure of embankment and crushing of the bearings, tilting of piers and deck portion of bridges. GSI (2003) carried out detailed macroseismic survey of the damage pattern of buildings, roads and bridges. Most of the damaged buildings were not properly designed and constructed as per Indian Standard Code. Structures founded on sound rocks like sandstone and basalt suffered lesser degree of damage than those on loose granular soil.

Krinitzsky and Hynes (2002) and Seed et al. (2002) studied behaviour of earth dams in the Kachchh area after Bhuj Earthquake and suggested remedial measures. The damages to earth dams were observed between isoseismal VII and X. Type of damages include longitudinal and transverse cracks in the central core, differential settlement, slumps/ slides, displacements, leakage and cosmetic minor cracks (Fig. 5).

EVALUATION OF DAMAGES OF EARTH DAMS

Re-evaluation of damages of earth dams has been done to assess the impact of ground shaking and geology on these structures. There are about 185 earth dams of minor and medium size in Kachchh district. Height of earth dams in general is below 20 m. These dams are founded on alluvial soil or weathered soft shale and sand rock with a core trench excavated to various depths depending on the availability of relatively hard layer. Design of these dams included an impervious core, a core trench with impervious fill, semi pervious (SP) shells, and riprap on the upstream face and at lower part of downstream face, downstream sand / gravel filter, and downstream boulder rock toe. In some of the dams short concrete core wall was provided embedded in cut-off (core) trench extending into the lower part of the impervious core.

Unconsolidated granular alluvial deposits and weathered soft sedimentary rocks form foundations of earth dams. Availability of Standard Penetration (SPT) test data for dam sites is limited to a few dams namely Chang, Rudramata, Tapar, Fategadh, Shivlakha, Ratia, Natharkui, Adhoi-II, Kankavati, Lotia, Wamka, Kaswati and Suvi dams. Theses tests indicated presence of loose granular alluvium up to 5m depth, with N-values ranging from 6 to 19. Below this depth N-values are greater than 25. Estimated earthquake shaking at the dams ranged from 0.2 to 0.7 g for PGA in the free field (Krinitzsky and Hynes, 2002). These indicate ideal conditions for liquefaction of foundation soils where ground water occurs at shallow depth.

About 15 dams of Kachchh and a few of Northern Saurashtra have suffered earthquake damage ranging form minor superficial cracks (isioseismal VII) to severe damage (isoseismal X) (Fig. 5). Chang dam which is located about 5 km NE from the epicenter of Bhuj Earthquake in isoseismal X suffered severe damage (almost collapsed) in the deepest river bed section (Fig. 5). Large fissures developed sub-parallel to the crest, are present on both the upstream and downstream faces. Along a few transverse cracks differential settlement of rip rap blocks was observed. In the river section slumping (slides) pulled apart dam crest causing collapse of structure in horst and graben fashion. Masonry core wall was also damaged. Minor damage to upper part of intake tower was observed. Evidence of liquefaction-related ejecta (“sand boils”) and toe bulging at both the upstream and downstream were observed (Seed et al., 2002). Shivlakha dam located at 39km E in isoseismal IX suffered almost identical damage in the upstream but damage of the downstream slope was minor in the form of toe bulging only. Generally upstream slopes suffered more damage than downstream slopes as the soil at the downstream of cut off trench was not fully saturated.

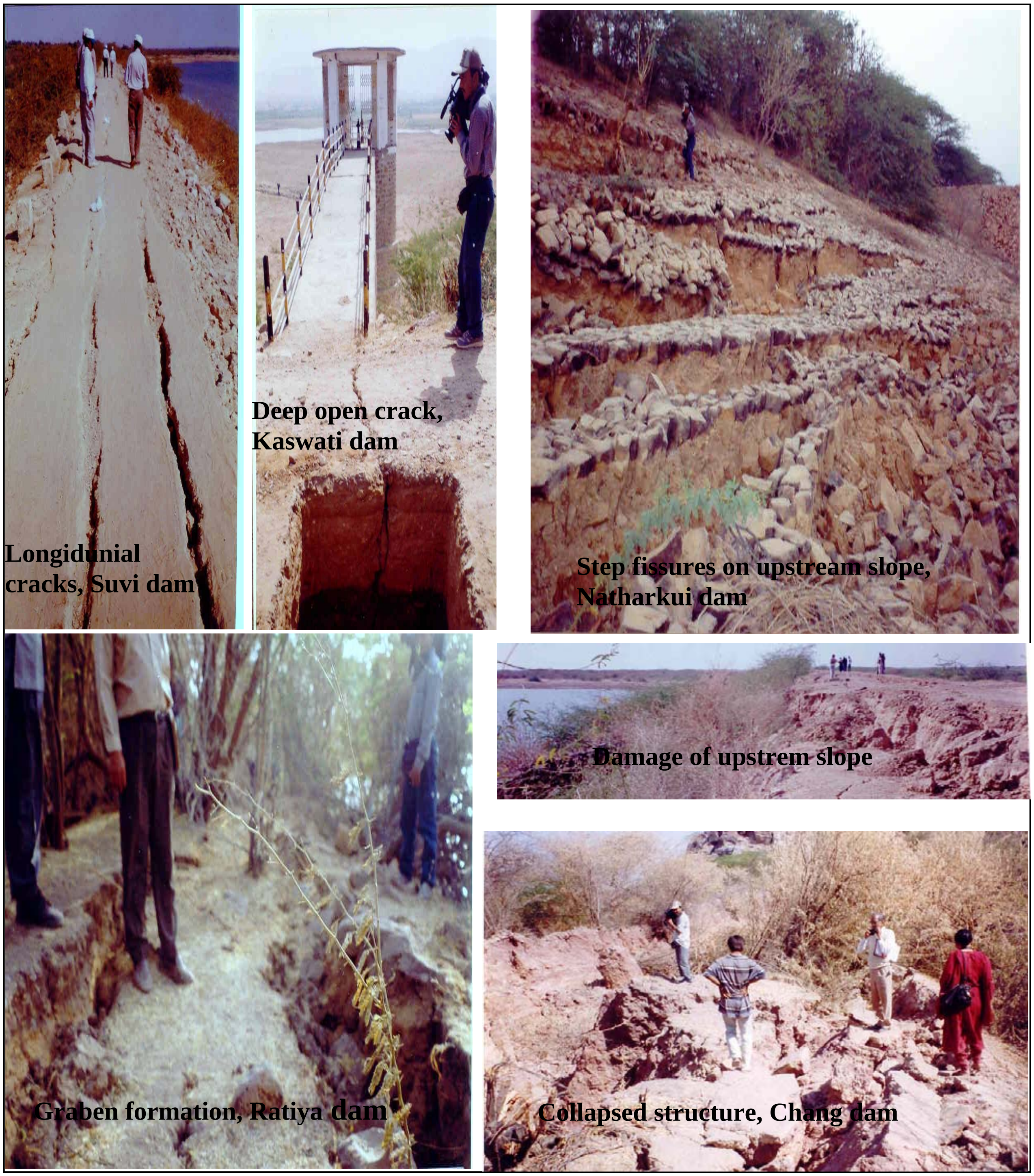

Fig.5. Types of co-seismic damages of earth dams in Kachchh

Multiple longitudinal fractures along the crest of the dam, with tensional displacements of the fractures were also observed in the Fatehgadh, Kaswati, Tapar, Suvi, Niruna, Rudramata dams falling in isoseismal IX. Other dams suffered similar type of damages with slight variations depending on the location, type of soil and water saturation condition (Fig. 5). Dams located in isoseismal VIII suffered relatively minor damages.

Krinitzsky and Hynes (2002) correlated degree of damage due to liquefaction at the dams with the level of shaking and suggested that Peak Horizontal Acceleration (PHA) of 0.20g in the free field, is a level at which a properly built dam, constructed on alluvium and susceptible to liquefaction can be considered safe, at 0.30g unsafe, at 0.50g hazardous and at 0.70g dangerous.

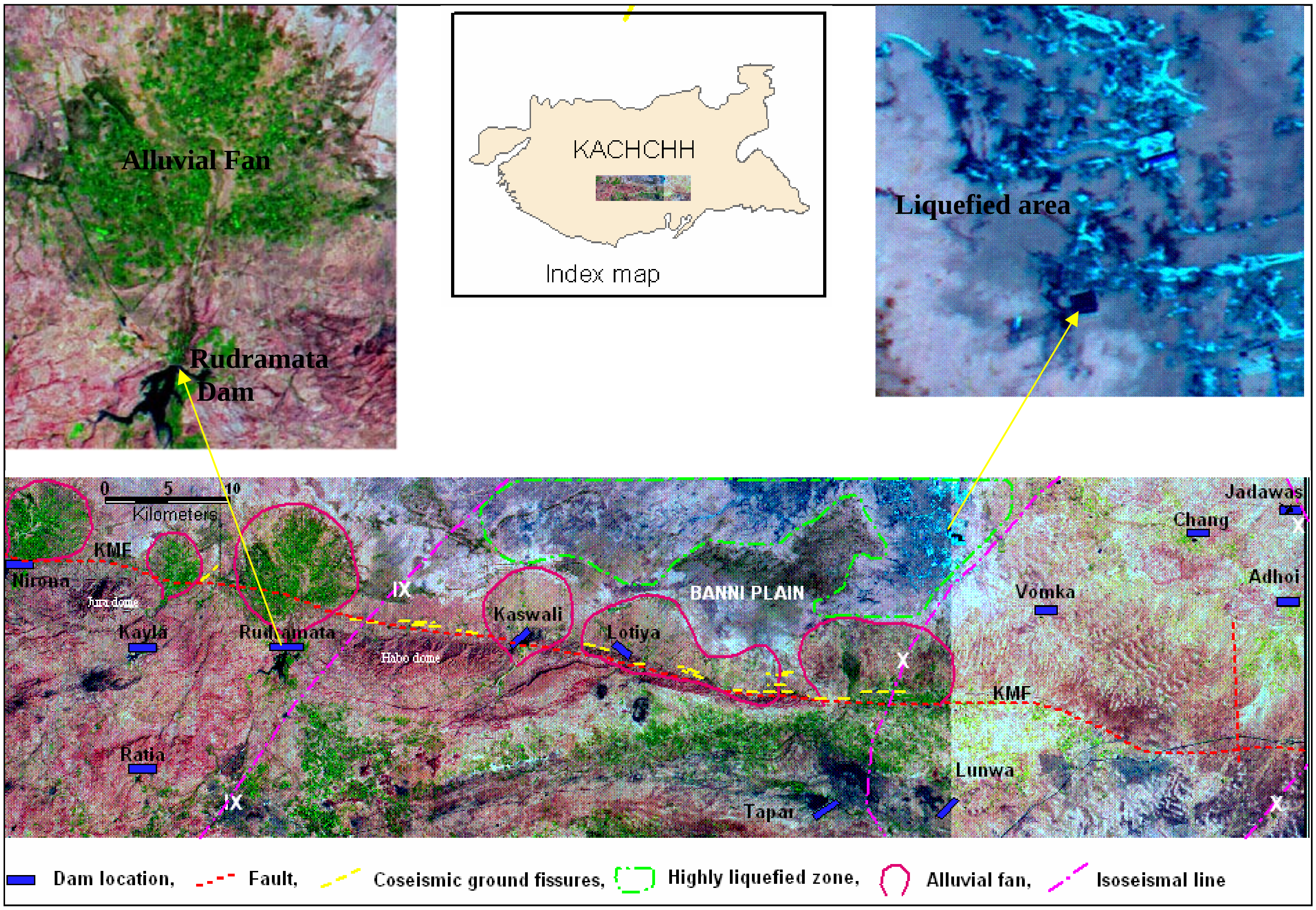

Fig. 6. Imagery showing co-seismic ground deformation, locations of damaged earth dams (in isoseismal IX and X) along and adjacent to Kachchh Mainland Fault (KMF) and liquefaction zone (Banni Plain)

Most of the earth dams showed longitudinal and transverse cracks on the top and on upstream or down stream slope of the dams varying in width from less than a centimeter to few centimeters. Conspicuous longitudinal cracks occurred in the earth dam's crest even in intensity VII where central core was constructed as thin masonry wall. It has been observed that, except Tapar dam, longitudinal axis of all earth dams in the area is roughly aligned in E-W direction as rivers are flowing in N-S or S-N direction. Incidentally, alignment of dam axis and longitudinal cracks developed in the dams are parallel to major Kachchh Mainland Fault (Fig. 6). Transverse cracks in the dams are also following major NE-SW and NW-SE lineaments.

TECTONIC INFLUENCE ON THE DAMAGE PATTERN

The Kachchh basin has a typical fault system generated during the initial phase of its origin. Mathew et al. (2006) observed diffuse aftershock pattern in the case for Bhuj Earthquake indicating tectonic movement on any major master fault would result in disturbances of all other interconnected faults in the area. It has been noticed that damaged cities, townships and villages are aligned along the trends of the master faults of the rift system of Gujarat region (Fig. 2). Completely devastated Adhoi town is located near South Wagadh Fault whereas severely damaged Rapar town is located close to Gedi Fault. Damaged cities of Ahmedabad, Maliya, Surat, and Navasari are aligned in north-south Cambay Rift Zone. Damaged cities and villages in Northern Saurashtra and Gandhidham-Kandla area of southern Kachchh closely follow the E-W striking North Kathiawar Fault. The devastated cities of Bhuj, Bhachau, Anjar, Adhoi and Samakhiali, and other villages of eastern Kachchh are situated between Kachchh Mainland Fault and Katrol Hill Fault. It appears that the damage pattern has a preferred orientation along existing faults. It also indicates a role of wave-guide effect along fracture zones on damage of structures located even far away from the source (Biswas and Khatri, 2002).

Kayal et al. (2002) analyzed about 1500 after shocks events during the period January to April 2001 and observed that deeper events (depth > 15 km) show greater concentration along a NE-SW trend, where as shallower ones (depths < 10 km) cluster along NW-SE direction. These trends are parallel to Anjar-Rapar (A-R) and Bhachau lineaments, respectively. The NE aftershock trend shows the longest and most intense activity. Iisoseismal of maximum intensity X (MSK) is also aligned in the NE-SW direction i.e. parallel to the A-R lineament (Fig. 1 and 2). A similar trend was observed for the 1956 Anjar Earthquake (Tandon, 1959). NE direction is a direction of present movement of Indian plate. Collating the isoseismal data and aftershock data indicate role of plate movement in generating Bhuj Earthquake.

Faults in the area are almost aligned in E-W, NE-SW and NW-SE direction. Prominent ground fissures in the area are aligned parallel to KMF and in the direction of rupture of blind/ hidden causative fault i.e. in E-W to ENE-WSW direction (Fig. 6). Ground fissures developed near source are also aligned parallel to NE-SW and NW-SE transverse faults. Longitudinal cracks developed in earth dams in the Kachchh area are aligned parallel to KMF. This indicates that development of fissures/ cracks in the ground as well as in the earth dams are structurally controlled.

POST EARTHQUAKE TREATMENT OF EARTH DAMS

In general liquefiable soil has been removed from the foundation of some of the dams up to 3 m depth and replaced with suitable duly compacted soil. The entire earth dam structure of Chang dam in the river section has been reconstructed to withstand earthquake forces considering the Bhuj Earthquake. At Shivalakha dam upstream slid earth mass was completely removed and reconstructed. In other dams part removal and reconstruction of loosened SP material and dislodged rip rap blocks have been done depending on the area of damage. Loading berms on the upstream and/ or downstream side of dams have been provided besides flattening of slopes wherever found necessary (Fig. 7). Longitudinal and transverse open fissures/ cracks were treated by back filling with compacted soil.

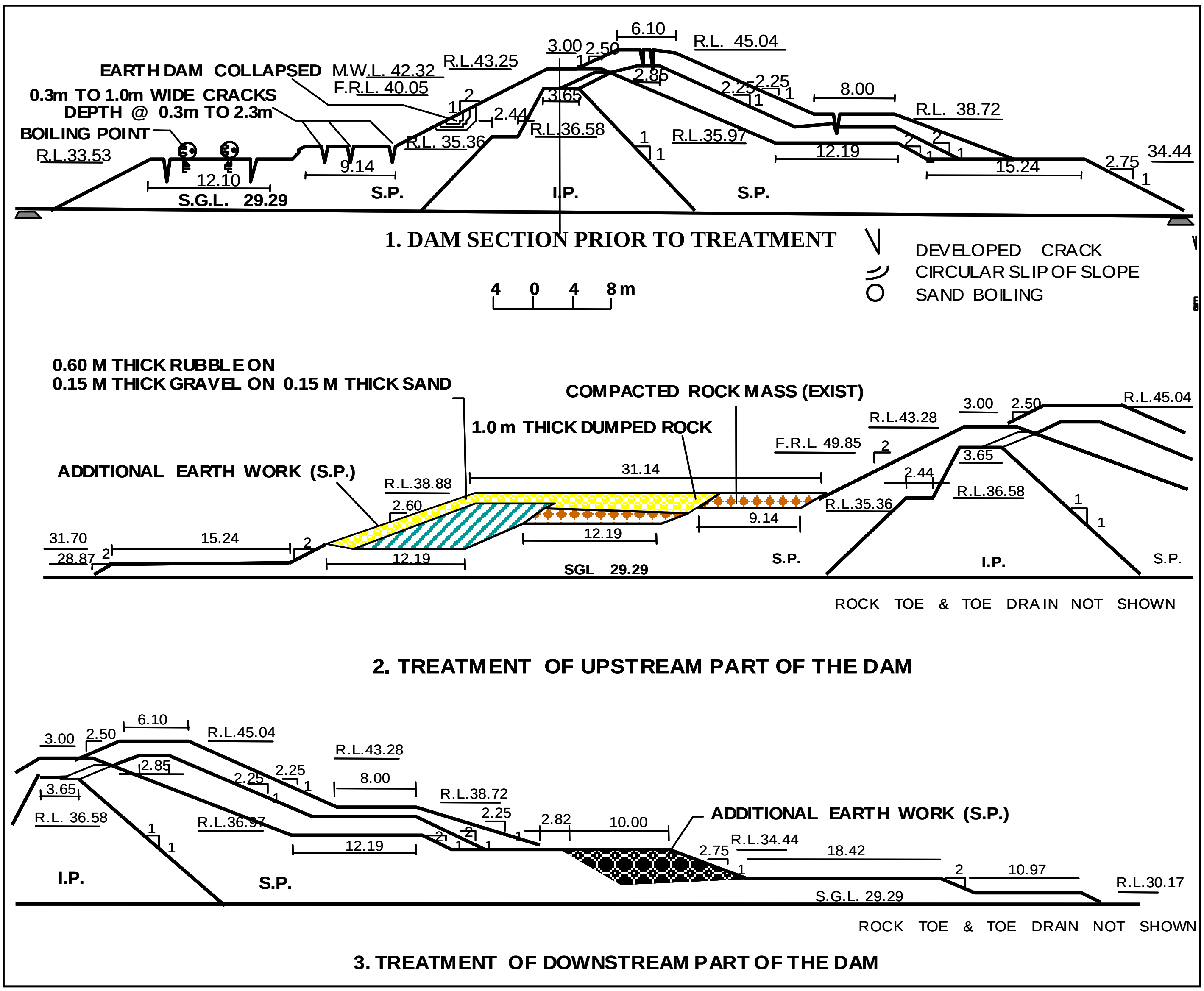

Fig 7. Sections of Tapar earth dam showing damage pattern and post earthquake treatment

CONCLUSIONS

Earthquake induced liquefaction of saturated granular foundation soil was the main reason for the damage suffered by most of the structures. The Bhuj Earthquake induced coseismic structural (tectonic) ground deformation parallel to Kachchh Mainland Fault (KMF) and along major transverse lineaments. Longitudinal cracks developed in earth dams in the Kachchh are also aligned parallel to KMF. These observations indicate structural influence on the development of fissures/ cracks on the ground as well as on the earth dams besides liquefaction of ground and foundation soil.

Structures founded on sound rocks like sandstone and basalt suffered lesser degree damage than those on loose granular soil. In general structures which have not been designed and constructed considering their location in seismic zones (III to V) were unable to resist seismic forces and suffered variable damage. Earthquakes of magnitude ± 5 are still continuing in Kachchh between KMF and Gedi Fault even after seven years of Bhuj Earthquake indicating activeness of this intra-continental area requiring detailed seismological and seismotectonic studies.

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REFERENCES

Bilham, R. [2001], "Intraplate earthquakes and flexure of the Indian Plate", Abstract Volume, *Internataional Conference on Seismic Hazard with Particular Reference to Bhuj Earthquake of Jan., 26, 2001*., pp. 352-353.

Biswas, S.K. and K.N. Khatri [2002], "A Geological Study of Earthquakes in Kutch, Gujarat, India", *Journal of Geological Society of India*, Vol. 60, pp.131-142.

Biswas, S.K. [2005], "A Review of Structure and Tectonics of Kutch basin, Western India, with Special Reference to Earthquakes", *Current Science*, Vol. 88, No.10, pp.1592-1600.

Gaur, V.K. [2001], "The Rann of Kachchh Earthquake, 26 January 2001", *Current Science*, Vol. 80, No. 3.

GSI [2003]. "*Kutch (Bhuj) Earthquake 26 January 2001*", Special Publication No. 76, Geological Survey of India, Lucknow, India.

IS 1893 (Part 1) [2002], "*Criteria for Earthquake Resistant Design of Structures Part 1 General Provisions and Building*", Bureau of Indian Standard, New Delhi, India.

Iyengar, R. and R. Kanth [2006], "Strong Ground Motion Estimation During Kutch, India Earthquake", *Pure Applied Geophysics*, Vol. 163, pp. 153-173.

Kayal, J.R. et al. [2002], "Aftershocks of the 26 January, 2001 Bhuj Earthquake in Western India and its Seismotectonic Implications", *Journal Geological Society of India*, Vol., 59, pp. 395-417.

Krinitzksy, Ellis L. and, Mary E. Hynes [2002], "The Bhuj, India, Earthquake: Lessons Learned for Constructing Dams on Alluvium", *Journal of Engineering Geology*, Vol. 66, Issue 3-4, pp. 163-196.

Lambe, T. William and Robert Whitman [1969], "S*oil Mechanics*", John Wiley & Sons, Inc., New York

Mathew et al. [2006], "Luminescence Chronometry and Geomorphic Evidence of Active Fold Growth along the Kachchh Mainland Fault (KMF), Kachchh, India: Seismotectonic Implications", *Tectonophysics*, Vol. 422, pp.71-87.

McCalpin, J.P. [1996], "*Paleoseismology*", Academic press New York, pp. 588.

McCalpin, J.P. and M.G. Thakkar [2003],"2001 Bhuj-Kachchh Earthquake: Surface Faulting in its relation with Neotactonics and Regional Structures, Gujarat, Western India", *Annals of Geophysics* Vo. 46, No.5, pp. 937-956.

Mehta, P.N. and, I. Prakash [1982], "Experience in Seismotectonic Investigations for the Evaluation of Design Earthquake for Major Engineering Structures, W. India", *4th International Congress International Association of Engineering Geology, India*, Vol. VIII, pp.87-96

Parvez, Imtiyaz A. and K. Madhukar [2006], "*Site Response in Ahmedabad City Using Microtremor Array Observation: A Preliminary Report*", Centre for Mathematical Modeling and Computer Simulation (C-MMACS), pp. 45

Rajendran et al. [1998], "Surface deformation related to the 1819 Kachchh Earthquake evidence for recurrent activity", *Current Science*, 75(6), pp. 603-626.

Rastogi, B.K. [2001], "Earthquakes in India-Causes-Effects and Issues", *Journal of Indian Building Congress*, Vol. VIII, No.1, pp. 83-93.

Rastogi, B.K. et al. [2007], "Microzonation of Vulnerable Areas of Gujarat", *National Seminar on "Seismic Microzonation", Gujarat State Disaster Management (GSDMA), India*, pp.8-19.

RaviShankar [1995], "Fragmented Indian Shield and Recent Earthquakes", *Geological Survey of India*, Spl. Pub. Vol. 27, pp.41-48.

Schweig, E. et al. [2002], “The Mw 7.7 Bhuj Earthquake: Global Lessons for Earthquake Hazard in Intra-Plate Regions” *Journal Geological Society of India*, Vol., 61, pp. 277-282.

Seed, R.B. et al. [2002],"Ground Failure and Geotechnical Effects: Dams," Chapter 9 of the Report on the January 26, 2001 Bhuj (India) Earthquake, Spectra, *the Professional Journal of the Earthquake Engineering Research Institute*, Vol. 18, Supplement A, pp. 131-146.

Tandon, A. N. [1959], “The Rann of Kutch Earthquake of 21 July, 1956”, *Indian Journal of Met. Geophysics*, Vol.10, pp.137-146.