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EFFECTS OF LOCAL GEOLOGY ON DAMAGE SEVERITY DURING BHUJ, INDIA EARTHQUAKE

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SUMMARY

This paper presents the effects of local geology on the damage severity during Bhuj earthquake of January 26, 2001. Bhuj earthquake (Mw=7.6) caused a heavy toll of about 20,000 dead, more than 60,000 injured, 200,000 people homeless, and more than U.S. $ 2.0 Billion in losses. Macroseismic field observations revealed that loose soil cover (Rann area) and topographical feature like ridge and island have played a significant role in damage. The damage patterns illustrate the strong influence of local geology conditions on the severity of the damage at many places like soil amplification in Ahmedabad, Morbi city, Ludra-Bhawar and low lying areas with thicker alluvium deposits; ridge effects on the Ramdev Pir hill near Hawai, Kutri village and Sajan Garh fort constructed on a hill near the Udaipur city and island effects at Beyt-Dwarka. Findings of numerical simulations of characteristics of seismic waves on the weathered hill supports the observed more damage on the Ram Dev Pir hill. Surface ground fissures and liquefaction were observed mainly in the swampy and Rann areas and heavily alluviated low land regions. Overall lesser intensities were observed in the hard rock areas that are mostly in the Deccan Traps, while higher intensities were observed on the alluvium soil cover at places like all of Rajasthan, the part of Gujarat to the north and east of the epicentre, and the coastal regions. It was concluded on the basis of the observation that local geology rather than engineering features of structures largely determined the severity of damage during the earthquake.

INTRODUCTION

Introductory material Bhuj earthquake of magnitude M_w 7.6 (USGS) of January 26, 2001 left a trail of death and devastation in Gujarat. The earthquake caused a heavy toll of about 20,000 dead, more than 60,000 injured, 200,000 people homeless, and loss of more than Rs. 10,000 crores. The epicentre of this earthquake (23.40° N, 70.3° E) was located about 10 km northeast of the Bachau city, Kutch district of Gujarat. The focal depth was estimated to be 25 km (USGS). This earthquake was felt up to Kashmir in the north, Kanyakumari in the south, and Nepal and Calcutta to the northeast. The most affected cities were Bachau, Bhuj, Anjar, Rapar, Gandhidham and Kandla city of Kutch district. The distribution of earthquake intensity was sporadically high; at some places attaining a maximum of X. Intensity X was observed at Bachau, Chobari, Manfara, Kobrau and Dudhai in the epicentral region.

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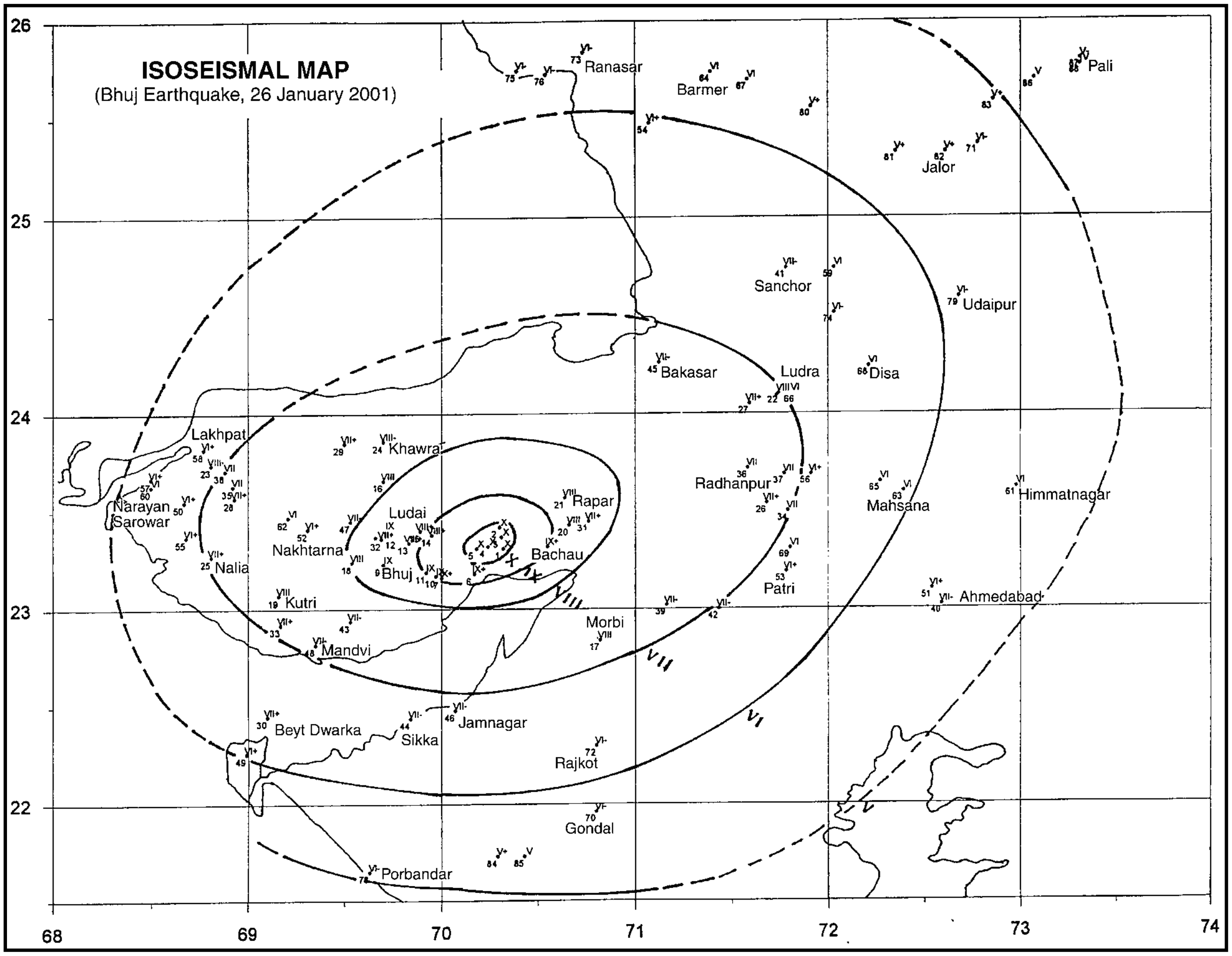

Fig. 1 Isoseismal map of Bhuj earthquake of January 26, 2001,(After Narayan [1])

The general observations as reported by many people in the affected area are mainly sound before the earthquake, and dizziness accompanying the earthquake shaking. Seaquake activity (a train of compressional waves refracted steeply upward from the sea bed) was reported by many fishermen onboard ships in the Sikka and Okha port regions. The anomalous behaviour of animals was reported at many places, such as fish jumping up to 3 feet above the water surface in Pushkar Sarowar (lake), Rajasthan. Devastation of many buildings in the meizoseismal area was observed (Fig. 2a). The level of shaking was very intense, and many of the reinforced concrete (RC) multi-storeyed buildings collapsed due to failure of ground floor columns (Fig.2b) The Bachau railway station collapsed, and the railway line near it suffered slight bending. Many water tanks in the area suffered heavy damage with a few of them totally collapsed. Underground water pipeline were broken at many places like Chobari and Deshalpar. The epicentral region experienced prominent vertical ground motion as evidenced by uprooting of the debris used as filling material for the divider of road in Bachau. Some of the observations, like those of the gushing of fresh water in areas where it is normally salty, increases of ground water levels and dominant vertical strong ground motion, were also reported in the Kutch earthquake of June 16, 1819 (Oldham [2]). The following sections describe the geological deformations and local site effects observed during the Bhuj earthquake.

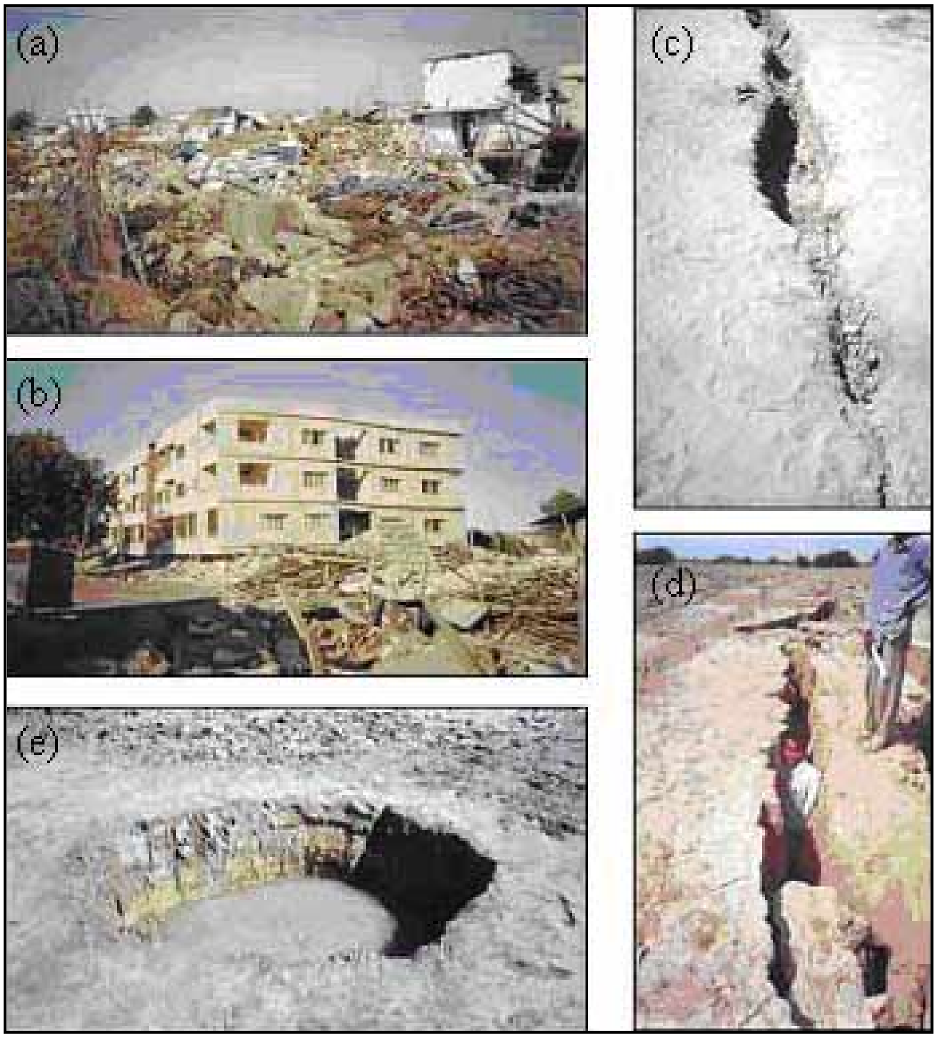

Fig. 2a. Destroyed Ratnal village,
b. Collapsed of ground floor of a RC building in Bachau,
c. Ground fissure oriented in the east-west direction in Dhrang village (20 km N-W of Bhuj),
d. Ground fissure oriented in the N-S direction in Chobari village (12-15 Km North of Bachau,
e. Violent geyser developed an elliptical ground hole in Khengarpar near Ludai village.

GEOLOGICAL DEFORMATIONS

The spatial distribution of the intensity and isoseismal map for the Bhuj earthquake of January 26, 2001, based on the damage survey, is given in Figure 1. Analysis of isoseismal map reveals that some of the localities have higher intensity as compared with the surrounding. Ground fissures associated with geysers and liquefaction (i.e. Kandla Port) were observed mainly in the swampy and Rann areas and in the heavily alluviated low land region in the meizoseismal area. Ground fissures were surficial in nature and were secondary effects i.e. not directly associated with the earthquake rupture. Deep and wide ground fissures were observed at many places like ground fissures oriented in the east-west direction about 2-3 km east of the Dhrang village (Fig. 2) and in north-south direction in the Chobari and Manfara villages (Fig.2d). Two violent geysers causing elliptical holes (3.4x4.3m) were observed between Khangarpar and Shrawan Kawara near Ludai, and the height of intermittent water flow was of the order of 6 to 7 m (Fig 2e).

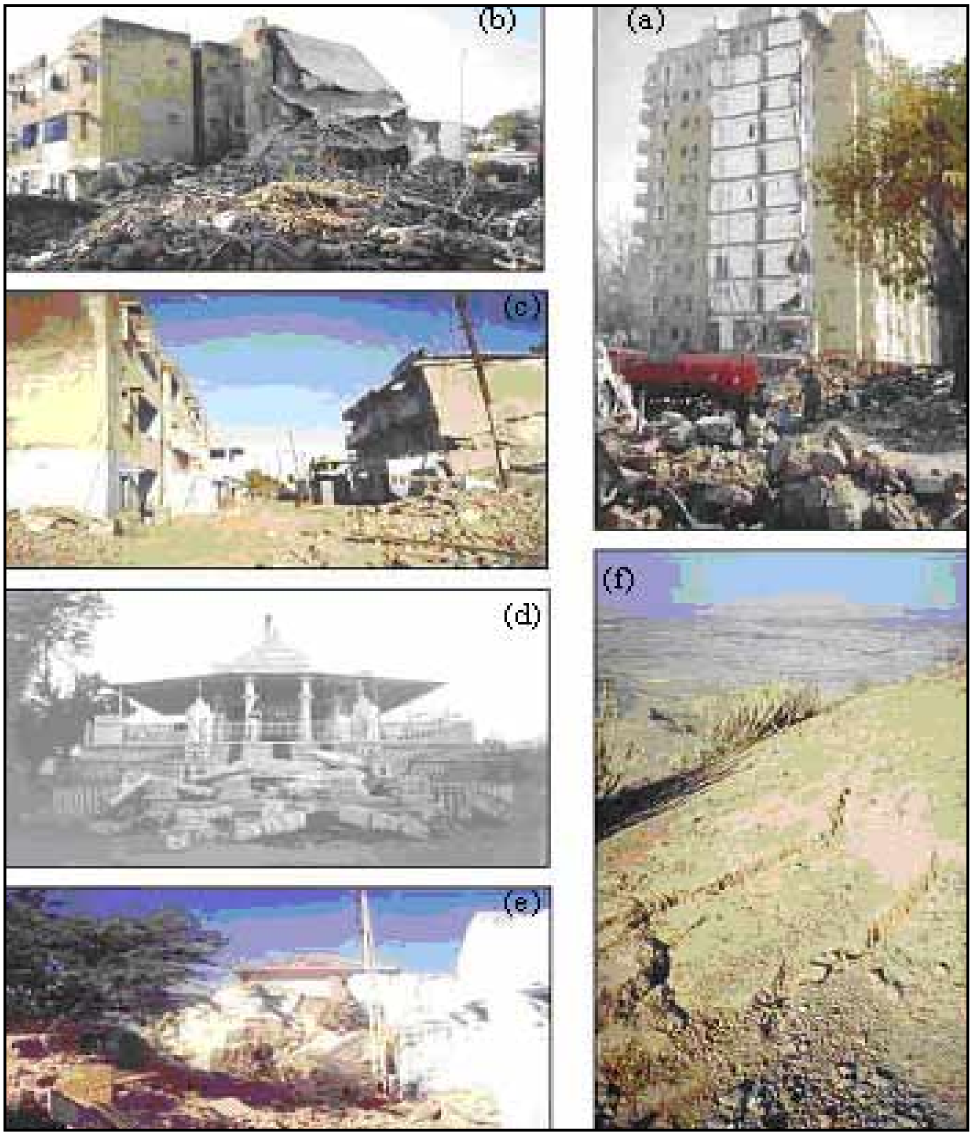

Fig. 3a. Total collapse of Block D of the Shikhar apartment building in Ahmedabad. The debris is being removed,

b. Collapsed B-type three storey building of Gujarat Housing Board in the Morbi city,

c. Severely damaged Gujarat Housing Board colony of Morbi city,

d. Damaged gate of newly constructed Jain temple in the Bhawar village,

e. Collapsed temple of Ludra village and

f. Parallel ground cracks oriented in the east- west direction on Ramdev Pir hill, 3 km away from the Hawai village.

LOCAL SITE EFFECTS

The most intense shaking experienced during earthquakes generally occurs near the ruptured fault, and decreases with distance away from the fault. In a single earthquake, however, the shaking at one site can easily be 10 times stronger than at another site, even when their distance from the ruptured fault is the same (Aki [3] and Geli [4]). Scientists have assumed that local geologic conditions are the cause of this difference in shaking intensity, but they have not been certain of the particular conditions that are most responsible, and the degree to which they affect earthquake shaking. Combining this information with estimates of where and how often earthquakes will occur would allow for better estimates of how intense shaking will be during future earthquakes.

Fig. 4a. Collapsed temple situated on the top of Ram Dev Pir hill,
b. Uprooting of water tank situated on the Ram Dev Pir hill and
c. Damaged Kutri village situated on an elevated ground

SOIL/BASIN EFFECTS

Strong basin effects on the ground motion characteristics were inferred in the form of intense damage observed during the Bhuj earthquake at many places (Narayan [1]). The effect of low frequency amplification caused by Sabarmati river basin (west of Ahmedabad) can be clearly seen in the form of severe damage to high-rise buildings (≥4 story) in Ahmedabad, situated about 350 km away from the epicentre. In Ahmedabad, most of the one and two story mud and brick houses were undamaged, with only few houses suffering minor cracks, while fifteen multi-storeyed buildings collapsed due to failure of the ground floor columns (Fig. 3a). There were about 65 such buildings (≥4 story) that suffered severe damage to the columns of the ground floor and were declared unsafe for habitation. The scatter of collapsed multi-storey buildings throughout the city of Ahmedabad show that the damage may not be purely attributed to the poor quality construction materials and the inadequate designs since there was relatively lesser damage in similar types of buildings having fewer stories. It may be inferred that soil amplification of lower frequency ground motion in the Sabarmati river basin caused greater damage to high rise buildings as compared to smaller ones, probably due to double resonance effects (Graves [5]).

The effect of unconsolidated soil cover was evident from the comparatively heavy damage to the Gujarat

Table 1: Parameters of different weathered layers

		V_s (m/s)	V_p (m/s)	Dens. g/cc
Weathering materials on the ridge	Soil ‘A’	400.0	1800.0	1.90
	Soil ‘B’	600.0	2000.0	1.95
	Soil ‘C’	850.0	2200.0	2.15
	Soil ‘D’	1250.0	2643.0	2.35
	Soil ‘E’	1620.0	3034.3	2.40
Rock Type	Softer	2000.0	3464.1	2.50
	Hard	2200.0	3810.5	2.60

Housing Board colony and its surrounding region in the Morbi city. Most of the three story brick buildings of this colony suffered severe damage (partial collapse) and a few collapsed completely (Fig. 3b,c). The effect of unconsolidated soils was also observed in the Ludra and Bhawar villages (Fig. 3d,e). Severity of damage in these villages was of the order of intensity VIII, whereas it was VI in the nearby town of Dyodhar (5 and 10 km from Ludra and Bhawar, respectively). The heavy damage in Ludra and Bhawar may be attributed to very loose soil (more than a meter) overlying a harder soil layer, where the foundation of the single story adobe houses are very shallow, mostly within the loose soil layer.

Ridge effects

The effect of ridge topography on the amplification of ground motion was observed on approximately 100 m high Ramdev Pir hill near Hawai and Ludai villages. The ridge effect was inferred on the basis of the contrast in the severity of damage on the hill (intensity IX^+) and in the nearby Hawai village (intensity $VIII^+$). Hawai village is not located on the hill. Many deep and wide parallel cracks on the top of the hill and along the slope predominantly in north-south direction were observed (Fig. 3f).

The collapsed temple on the hill (Fig. 4a), shifting and uprooting of a water tank (Fig. 4b), and displacement and breaking of large boulders on the hill indicate amplification of the ground motion there. The walls of the temple located at the top of hill were thrown outward, and the dome of the temple fell down vertically at the same place. Strong damage to the hill mass itself in the form of long and deep ground cracks and uprooting of water tank and shifting and breaking of large rock boulders and collapse of the temple on the hill may be attributed to the ground motion amplification by the hill (Pedersen [6]; Narayan [7]). Further, amplification of the ground motion depends on the slope and the elevation of the ridge (Sánchez-Sesma [8]; Geli [4]). Ridge type effects were also observed at the Kutri village (Fig. 4c) and at Sajan Garh fort constructed on a hill near the Udaipur city.

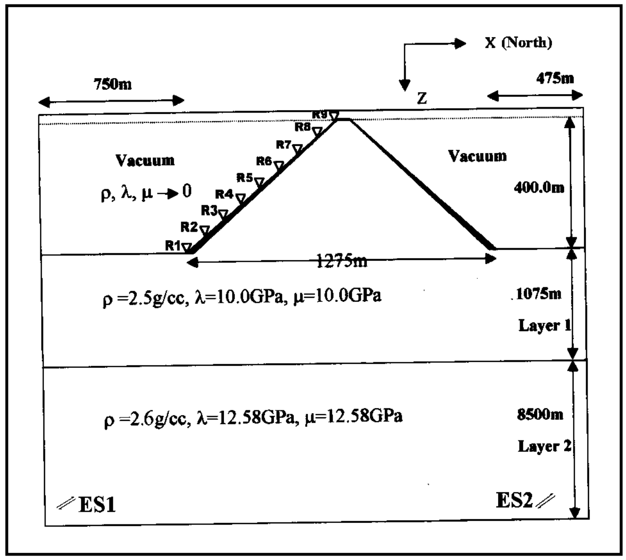

Fig. 5 Vertically exaggerated ridge model (After Narayan [9].

Table 2: Vertical weathering thickness beneath different recording stations.

Thickness of soil 'm'	Recording Stations								
	R1	R2	R3	R4	R5	R6	R7	R8	R9
	15	10	10	10	10	10	5	5	5

Deep cracks up to the base of the weathered hill mass, displacement of boulders reveals strong surface wave generation. These observations corroborates with the simulated response computed by Narayan [9] of a weathered ridge model shown in figure 5. Slope, height, width of top and base of the considered ridge model are 32.6°, 400.0 m, 25.0 m and 1275.0 m, respectively. Weathering material properties and thickness below the recording stations are given in table 1 and 2. Ridge model was simulated using a point shear dislocation earthquake sources with focal mechanisms as dip = 90^0, rake = 90^0 and Strike = 90^0 at focal depth of 9.475 km and at a distance of 0.89 km south of the ridge axis. The time step and dominant frequency were taken as 0.0005 s and 5 Hz, respectively. Figure 6 shows the radial component of ground displacement for both weathered and non-weathered ridge cases. Surface waves were developed in both the weathered and non-weathered ridge cases, somewhere near the top of the ridge.

The amplitudes of surfaces waves are decreasing towards the top and base of the ridge except for soil ‘A’ where amplitude and duration of surfaces waves are very large and increasing towards the base of the ridge. We conclude that soft weathered materials of the Ram Dev Pir hill may have generated very large amplitude surface wave with longer duration, causing collapse of the temple and damage to hill mass itself in the form of deep ground cracks, shifting and breaking of large boulders.

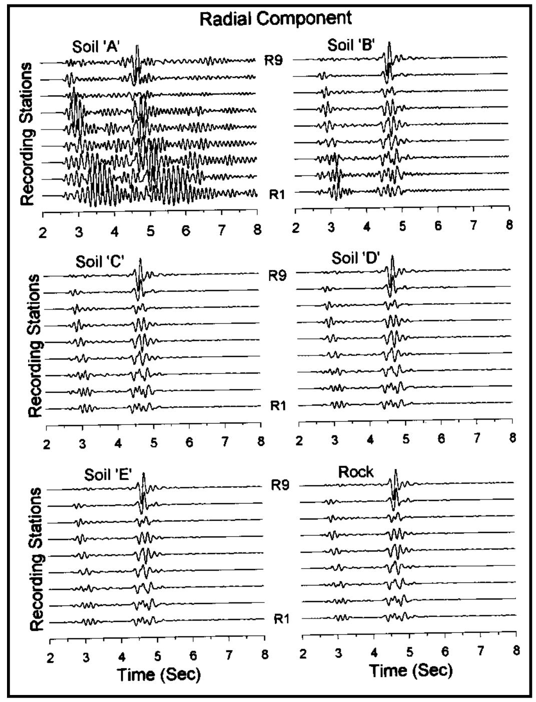

Fig.6 Radial component of the ground motion along the slope of ridge for different weathering-velocity.

Island effects

Island effects on the ground motion characteristics were inferred on the basis of contrasting damage observed in Beyt Dwarka island, 2 km away from the Okha port. The intensity of shaking in Beyt Dwarka was of the order of VII$^+$, whereas it was only VI$^+$ in nearby Okha port. The average height of the island with respect to mean sea level is about 8 meters, spanning an area of about 36 square km. More than 50% of the buildings on this island were destroyed, and most of the existing buildings are unsafe for habitation. According to Hindu mythology, the Beyt Dwarka temple was the place of residence for Lord Krishna and his four wives, Lakshmi, Satya Bhama, Radhika and Jamwanti.

The residences of the four queens of Lord Krishna situated on the first and second floor of the Beyt Dwarka temple (500 years old) were partially collapsed. However, the ground floor constructed on a wooden frame suffered no damage, and the 5,000-year-old idol of Krishna was safe. Figure 7 shows the damage to Beyt Dwarka temple. The very old and traditional Jetty of Beyt Dwarka suffered damage in the form of falling of the parapet, cracks and subsidence (5-8cm) at one place. On the other hand, Okha suffered almost no damage and only fine/minor cracks were observed in some of the weak houses. The reasons behind the longer duration of shaking, and severe damage to buildings on Beyt Dwarka island may be due to ground motion amplification, surface wave generation and their trapping by the weathered surfacial layer of the island.

Fg. 7 Severely damage Beyt Dwarka temple.

CONCLUSIONS

The damage patterns during Bhuj earthquake of January 26, 2001 revealed strong influence of local site conditions on the severity of the damage at many places. Ground fissures associated with geysers and liquefaction were observed mainly in the swampy and Rann areas and in the heavily alluviated low land region in the meizoseismal area. Ground fissures were surficial in nature and were not directly associated with the earthquake rupture. Severe soil amplification effects were observed in the entire Rann area, Morbi city, and in the Ludra and Bhawar villages.

Low frequency amplification associated with the Sabarmati river basin and matching of this frequency with the natural frequency of the buildings (means double resonance) might be the reason behind heavy damage to taller building as compared to smaller buildings in Ahmedabad city, 350 km away from the epicentre. Island effect was inferred based on severe damage to structures built on Beyt Dwarka island, 2 km away from the Okha port, but only minor damage to structures situated on the Okha port. Ridge effects (ground motion amplification and surface wave generation) in the form of strong damage to the hill mass itself (long and deep ground cracks), uprooting of water tank, shifting of large rock boulders and the collapse of the temple on the Ramdev Pir hill near Hawai village was observed.

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REFERENCES

1. Narayan, J.P., Sharma, M.L., Ashwani Kumar “A seismological report on the 26 January 2001 Bhuj, India earthquake”. Seism. Res. Lett., 2002, 73: 343-355.
2. Oldham, T. “A catalog of Indian earthquakes from the earliest times to the end of A.D. 1869”. Geological Survey of India, 1883, Memoir X.
3. Aki, K. “Local site effects on strong ground motion”, in “Earthquake Engineering and Soil Dynamics II- Recent advances in ground motion evaluation”, J.L. Von Thun (Ed.), Geotec. Spec. Pub., 1988 No. 20, 103-155, Am. Soc. Civil Eng. New York.
4. Geli, L, Bard, P.-Y., Jullien, B. “The effect of topography on earthquake ground motion: a review and new results”. Bull. Seism. Soc. Am., 1988, 78: 42-63.
5. Graves, R.W. “Preliminary analysis of long period basin response in the Los Angeles region from the 1994 Northridge earthquake”. Geophys. Res. Lett., 1995, 22: 101-104.
6. Pedersen, H., Hatzfeld, D, Campllo, M., Bard, P.Y. “Ground motion amplitude across ridges”. Bull. Seism. Soc. Am., 1994, 84: 1786-1800.
7. Narayan, J.P., Rao, M.V.P. “Two and half dimensional simulation of ridge effects on the ground motion characteristics”. Pure and Applied Geophysics, 2003, 160: 1557-1571.
8. Sánchez-Sesma, F.J., Bravo, M.A., Herrera, I. “Surface motion of topographical irregularities for incident P, SV and Rayleigh waves”. Bull. Seism. Soc. Am., 1985, 75: 263-269.
9. Narayan, J.P. “Simulation of ridge-weathering effects on the ground motion characteristics”. J. Earthquake Engg., 2003, 7: 447-461.