Effect of 26 January 2001 Bhuj Earthquake on Earth Dams of Kachchh District, Gujarat, India

Prabhas Pande*

Abstract

The Kachchh Peninsula is a unique seismotectonic unit of the Stable Continental Region of the Indian Subcontinent for the fact that it is the most dynamic seismic province, where earthquakes in excess of magnitude 7 have repeatedly occurred during the Holocene tectonic regime. For the associated seismic hazard, a major part of Kachchh falls in Zone V of the map showing Seismic Zones of India. Quaternary sediments, which generally lie marginally above the mean sea level and hold groundwater, both fresh and brackish, at shallow depths, occupy nearly 45% of the land surface of the district. Such a geotechnical subsurface environment has proved to be highly conducive for the development of large-scale liquefaction on strong seismic excitation. Many engineered structures of Kachchh district, including a large number of dams, rest over such fragile foundations. The 26 January 2001 Bhuj earthquake of magnitude 7.6 caused failure of different grades in 157 of these earthen structures, built to store the meagre rainfall for meeting the requirements of water of the district. The paper analyses the damage to some of the larger dams, and lays stress on conducting microzonation and liquefaction susceptibility studies, for a realistic seismic hazard assessment of the region.

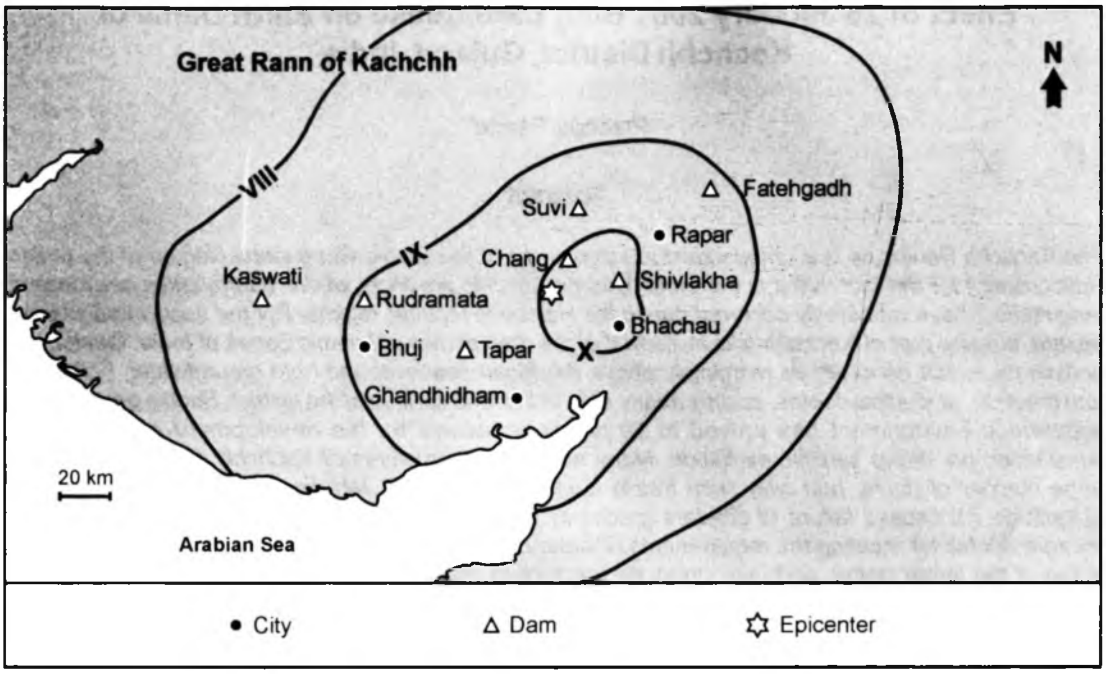
Introduction

The Kachchh Peninsula, forming the western most part of the Indian Landmass, is seismically, the most fertile intraplate region of the world, characterized by low earthquake recurrence rate at high energy level (Pande, 2007). The earthquake data, pertaining to the last two centuries, indicate that the annual average seismic energy release has been at the rate of 9.90 x 10^{20} ergs in this tectonic domain, which originated in the Mesozoic times as a pericratonic rift within a Precambrian basement. The region has imprints and history of occurrence of several destructive earthquakes. This rift zone has, thus, been included in the highest class of seismic hazard, comparable with some of the most active seismotectonic units of the Himalaya and other Tertiary mobile belts.

The 26 January 2001 Bhuj earthquake has been one of the deadliest seismic events of the Indian Peninsula, in which 13,805 human lives were lost, 1.77 lakhs injured and a total of 12,05,198 housing units partly or fully damaged in 16 districts of Gujarat state. The disaster caused an estimated overall loss of Rs 28,423 Crores. The brunt of the calamity was borne by five districts, viz, Kachchh, Ahmadabad, Rajkot, Jamnagar and Surendranagar, where 99% of the casualties and damage took place. From the neighbouring province of Sindh, Pakistan, 40 human casualties were reported. The maximum destruction was concentrated in Kachchh district, where, in the 949 villages of 10 talukas, 12,221 people were killed and 1,36,048 injured, despite involvement of a very low population density of 33-persons/sq km.

The 2001 earthquake had a magnitude (Mw) of 7.6 and a focal depth of 25 km. The macroseismic survey indicated the epicentral intensity of X on MSK-64 scale, encompassing an area of 780 sq km (Pande *et al.*, 2003a). In this zone, the damage to civil structures, including the engineered/semi-engineered ones, like dams, bridges, RCC framed buildings, etc., was near complete (Fig.1). 38% of the casualties occurred in this isoseist. The

*Geological Survey of India, Lucknow, email : prabhaspande@hotmail.com



isoseismal IX occupied a cumulative area of 10,455 sq km. Here also, most of the structures came under severe distress and became the cause of 54% of the casualties. Isoseismal VIII had a spread of 46,000 sq km, where the damage to buildings caused 4% of the fatalities. Within isoseismal VII, which enclosed a cumulative area of 1,40,000 sq km, heavy structural damage to a particular type of buildings occurred in urban agglomerations of Ahmadabad, Bharuch and Surat, located in thick Quaternary sediments along the Cambay graben. In this isoseist, 856 human casualties occurred.

A network of 13 Structural Response Recorders, installed by the Indian Institute of Technology, Roorkee (IITR), recorded the pseudo spectral acceleration (PSA) and peak ground acceleration (PGA) induced by the earthquake. It gave the maximum PGA of 550 cm/sec^2 at Anjar, followed by a value of 330 cm/sec^2 at Niruna. At Ahmadabad, the PGA was 130 cm/sec^2. A multi-channel digital strong motion accelerograph, installed at the base of a building in Ahmadabad by IITR, recorded a PGA of 106 cm/sec^2 (Kumar *et al.*, 2001). Using the empirical relationship of $\log A = Io/3$, the PGA in the epicentral zone was calculated as 681 cm/sec^2 by Pande (2007).

Physical Losses

The damage, consequent to the 2001 earthquake, spread in a very large area of the state of Gujarat. The direct losses, comprising loss of human lives, livestock, other animals, private property, municipal infrastructure, power-telecommunication infrastructure and health/educational assets, were to the tune of Rs. 15,308 Crores. The indirect losses, that included export/import, agricultural output, remittance income, fall in earning potential, unemployment and health hazards, were of the order of Rs. 3,048 Crores. The tertiary losses, accounting for long-term development, overall investment climate, funds reallocation and community migration/relocation, were to the extent of Rs. 10,067 Crores. The facilities that were impacted by the strong tremors can be categorized as i) reinforced concrete structures, ii) masonry structures, iii) heritage structures, iv) industrial facilities, v) Port infrastructure, vi) Railway infrastructure, vii) elevated tanks, viii) electric power system, ix) water supply system, x) roads-bridges, and xi) dams. The physical losses incurred are given in Table-1.

In Kachchh district, a total of 1,06,783 houses were damaged beyond repair in the rural sector. In the urban areas, comprising the towns of Bhuj, Mandvi, Anjar, Gandhidham, Bhachau and Rapar, 17,577 houses were severely damaged that required reconstruction. This mammoth task was accomplished with the involvement of a large number of NGO groups and Governments of other states (GSDMA, 2005). Various essential facilities, like water and electric power supply; telecommunication,

Table-1: Physical Losses in 2001 Kachchh Earthquake (After Arya, 2006)

S.No.	Facilities Affected	Impact	Number
1.	Houses	Fully collapsed/destroyed (G5/G4) Partly damaged (G3, G2, G1)	315000 928000
2.	Health Department buildings	Fully damaged Partly damaged	1229 2791
3.	Educational buildings	Primary Schools Teacher Training Institutes Secondary Schools Colleges Technical Education	9593 42 2040 47 58
4.	Public buildings	Destroyed Damaged	445 1973
5.	Police Department buildings	Destroyed Damaged	1267 5054
6.	Heritage structures	Destroyed Damaged (G3, G2, G1)	07 200
7.	Earth dams	Medium: major damage minor damage Minor: major damage minor damage	05 11 14 127
8.	Municipal infrastructure	Severe damage in town Moderate to minor damage in town	14 43
9.	Rural water supply	Villages severely affected	1100
10.	Electric power supply	Districts badly affected	05
11.	Transport infrastructure (bridges/culverts, Railway Stations and tracks, Kandla and Navlakhi Ports	Damaged	-
12.	Telecommunications	Collapse of telephone buildings	179
13.	Industry	Damaged/destroyed	-

etc., that were severely impaired in Kachchh district, had to be urgently restored.

Damage to Dams

A large number of engineered/semi-engineered structures came in distress under the influence of strong ground motions of the 26 January event. Moderate to heavy damage took place in intensity zones X and IX, particularly where the PGA exceeded 250 cm/sec^2. Away from the epicentre, in intensity VII and VI, the effect of the tremors to properly designed and constructed engineered structures, was negligible. Major dams, such as that of Sardar Sarovar, Karjan, Kadana and Panan, falling in isoseists VII and VI, though severely jolted, remained intact and functional. Kachchh district, being the epicentre, faced the maximum fury of ground agitation, which persisted for nearly a minute's duration in various frequency bands.

The Kachchh district receives an annual rainfall of 332 mm, with history of repeated monsoon failures and droughts. The low relief topography and semi-arid climatic conditions do not support the development of any perennial river system. The prominent south flowing streams, originating from the central highland of Kachchh and debouching into the Gulf of Kachchh, include Naira, Kankawati, Choke, Sie, Vengdi, Kherod, Rukmavati, Khari, Nagwanti and Sakra. The north flowing rivulets that disappear in the expanse of *Rann* (marshy and salt encrusted wasteland) are Nara, Panjarwati, Chhari, Bhukhi, Tramdo, Kaila, Pur and Kaswali. The requirements of water in the district, whether for drinking purpose or irrigation, are fulfilled through numerous low to medium height water retention structures, built across the ephemeral streams. There are, in all, 20 medium (reservoir capacities generally between 5 and 65 million cu m) and 165 minor (reservoir capacities of less than 4 million cu m) earth dams in Kachchh. The Republic Day earthquake caused damage to 16 medium and 141 minor dams. In most of the cases, the distress was on the upstream side of the shell portion. Since, almost all the reservoirs were at very low levels because of drought like conditions prior to the earthquake; unusual releases did not take place that could endanger the habitats of the command area.

The prime cause for failures of such a large number of dams, interspersed in an area of about 11,000 sq km, was liquefaction, which was observed to be profuse within isoseists X and IX (Pande *et al.*, 2003b). The phenomenon, a state in cohesionless soil, where the effective shear strength of the soil mass gets reduced to negligible value due to progressive increase in pore fluid pressure for reasons such as repeated or cyclic loading, as in case of an earthquake, was manifested in the form of sand blows/boils, fissures, craters, subsidence and lurching of ground. Where the contact between the liquefiable and overlying material was inclined even slightly, shear failure occurred, leading to predominantly horizontal shifting of the overlying mass. Such a phenomenon, referred to as 'lateral spreading', is explained in Fig.2. Structures founded over liquefiable sediments suffered severe distress during strong earthquake excitation.

Seven dams in Kachchh district, viz, Chang, Shivlakha, Tapar, Suvi, Fatehgadh, Rudramata and Kaswati, having comparatively larger reservoirs and falling in or around the meizoseist, suffered conspicuous distress (Fig.1). Other damaged dams, apart from the road-rail embankments, bridges, culverts and civil structures, that were studied in detail by the Geological Survey of India, included Brahmani, Mathal and Nara.

Chang dam, located close to the 2001 epicentre within isoseist X, experienced major failures. Its 370 m long and 15.5 m high earthen embankment, consisting of a central hearting of impervious fill, a central masonry core wall and the outer shell of semi-pervious earth fill, suffered major deformation under the influence

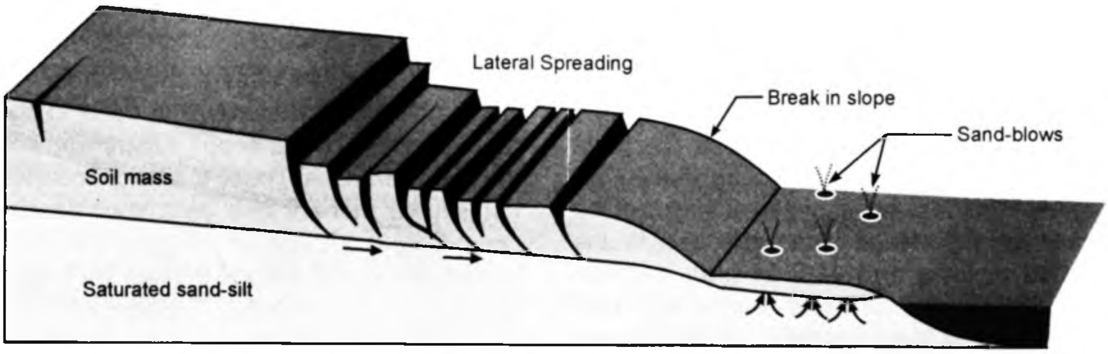


Fig. 2: Sketch diagram explaining the mechanism of lateral spreading (After Pande *et al.*, 2003b).

of strong and prolonged shaking (Figs.1 & 3). Severe liquefaction of the saturated sand-silt horizons, lying beneath the shell zone, caused large translational slides on the upstream slope, thereby pulling apart the central portion of the embankment (Seed, 2002). The crest portion, thus, dropped in a series of graben like blocks with maximum crest loss of 6.5 m. This slumping also produced a series of open fissures in the embankment. The repair of this heavily damaged structure was not feasible and so it had to be rebuilt.

The Shivlakha dam, also located within the epicentral tract, comprised a 300 m long and 18 m high earthen embankment for storage of the seasonal discharges. Sections of the structure slumped due to severe liquefaction of the founding strata in intensity X. The Tapar dam across Sang rivulet was constructed in 1976 and the dam height raised in 1990, to supply water to Gandhidham town and Kandla Port. This 1,350 m long and 18 m high earthen embankment, consisting of an impervious core with a shallow central key trench cut-off and a semi-pervious shell, was founded entirely over liquefiable alluvium. The intensity IX of the 2001 earthquake caused significant lateral spreading of the substratum that led to translational movements in the upstream face of the dam (Seed, 2002). Wide-open and vertically displaced fissures appeared at the crest

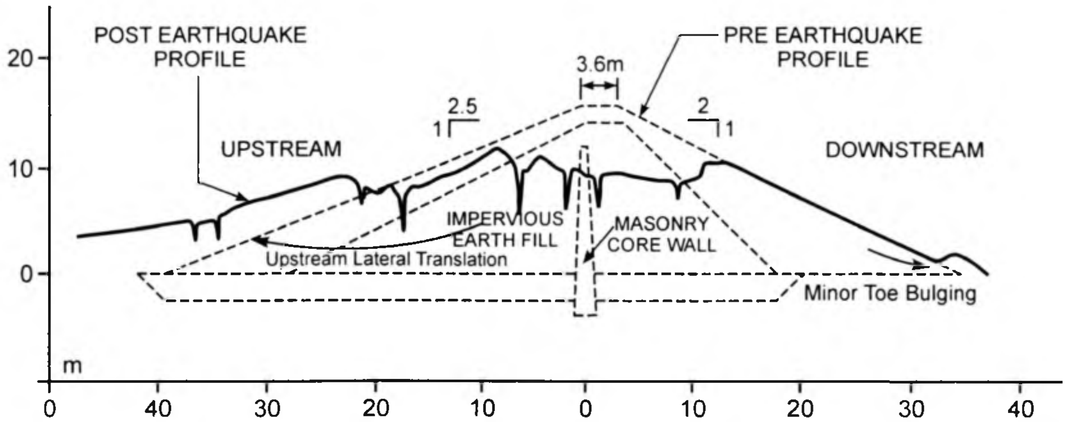


Fig. 3: Chang dam embankment section deformed consequent to 2001 earthquake (Modified after Seed, 2002).

portion. The 2,100 m long and 16.5 m high Suvi earthen dam was also subjected to an intensity of IX. As a result, slump fissures appeared on the upstream face of the shell slope. A stone masonry parapet, constructed at the crest portion, almost totally collapsed due to the strong vibrations experienced at the top of the structure. At Fatehgadh dam in isoseist IX, the 4,050 m long and 11.6 m high earthen embankment suffered slumping and consequent development of wide-open longitudinal fissures along the upstream shell slope, as well as considerable deformation in the dam profile.

The Rudramata and Kaswati dams, located to the west of the 2001 epicentre in intensities IX and VIII, respectively experienced lot of distress due to the passage of seismic waves (Fig.1). The 875 m long and 27.6 m high, Rudramata dam, built in 1959 across the confluence of Pur and Khari rivulets, has a reservoir storage capacity of 65 million cu m (Seed, 2002). The crest of this zoned earthen structure developed numerous open fissures, the opening being the maximum over the river channel sections. Joshi *et al.* (2003) reported development of a 2.0 m deep and 70.0 m long slump zone on the upstream face of the dam between the sluice and the central rivulet section. Leakage was also reported from the toe portion of the disturbed zone. At Kaswati dam, the upstream shell zone slumped in certain sections and longitudinal fissures appeared in the crest.

The 3,500 m long and 20 m high Brahmani dam across river Brahmani showed development of minor longitudinal fissures in the crest portion. The 2,250 m long and 13 m high Mathal dam suffered by way of differential settlement that led to dislodgement of upstream stone pitching, damage to headrace sluice and development of longitudinal and transverse fissures (Joshi *et al.*, 2003). The Nara dam, an arcuate earthen embankment, experienced differential settlement and dislodgement of pitching stones.

Concluding Remarks

The Kachchh district has a large number of water retention structures that cater to the requirements of water supply for drinking and irrigation purposes. These low height earthen dams have, more or less, a common design, comprising an impervious clay core with a low cut-off trench and a stone pitched shell zone of semi-pervious material. The dam slopes of relatively higher structures are provided with berms. The structures have invariably been founded over alluvium, where the groundwater occurs at shallow depths. The 2001 earthquake caused minor to severe damage to 157 of these embankments, creating serious shortage of water in the district, more so, because of impairment of water supply system, as well. It is apparent that in the design of these dams, very little attention was paid to the properties of the founding strata, particularly with regard to cyclic loading of the sediments. It is intriguing to note as to why this important factor of safety was overlooked even in the design of engineered structures?

One of the prime causes of damage to dams in Kachchh district was liquefaction propelled lateral spreading of the founding strata. The degree of severity of the phenomenon is governed by the amplitude and duration of cyclic loading, and so, more dependent on the magnitude of the seismic event rather than on the intensity observed at a particular place. It is inferred that the earthquakes in Kachchh of magnitude more than 6.5 may prove to be strong enough to give rise to large-scale liquefaction in geotechnically suitable conditions. Structures, resting over liquefiable foundations, can experience small to large translational movements/differential settlements, and so, are liable to undergo deformation and failure. Several of the dams, highway-railway embankments, Port infrastructure, etc., of Kachchh district are founded over such material.

The Quaternary deposits of fluvial, aeolian, marine or mixed origins occupy majority of the surface area of Kachchh district. A large number of civil structures, including many of the important buildings, as well as the engineered structures, are founded over such young deposits, having the properties of low shear wave velocity, low N-value, low density and high permeability. This tectonic belt is dissected by a number of faults and fractures, which could be seismogenic in nature and having the potential to reactivate in the event of seismotectonic perturbations. These factors make the Kachchh district, and for that matter, many of the urban agglomerations of Gujarat, like Ahmadabad, Bharuch, Surat, Porbandar, etc., domains of selective amplification of ground motions. In all the hazard analyses, the PGAs have been derived for hard rocks. Thus, necessary increments in the acceleration values need to be applied in the designs, particularly of the sensitive structures. For normal structures, the Seismic Design Codes provided by the BIS should be strictly adhered to.

It is considered imperative to carry out systematic seismic microzonation and liquefaction potential studies of the vulnerable urban agglomerations of Gujarat so as to assess the seismic hazard in realistic terms. Site-specific geotechnical investigations are required for providing earthquake resistant designs to all the engineered structures in Kachchh district.

Acknowledgements

The author is grateful to Dr. P.N.Razdan, Deputy Director General, GSI, NR for according permission to publish this paper.

References

Arya, A.S. (2006): Mitigation of earthquake risk in India-the road ahead. 13 SEE-06, Earthquake Engineering, Roorkee. Vol. II, 1159-1170.

GSDMA (2005): Houses reconstructed by NGOs in Gujarat and Kachchh district. Govt. of Gujarat, www.gsdma.ord/pdf/ngo-talukas.pdf.

Joshi, Y.C., Harendranath, L., Venkatraman, N.V. and Basu, A.K. (2003): Damage to engineered structures. P.Pande and J.R.Kayal (Eds.). Geol. Surv. India Special Publ. No. 76, 155-161.

Kumar, A., Basu, S., Thakkar, S.K., Shrikhande, M., Agarwal, P., Das, J. and Paul, D.K. (2001): Strong motion records of Bhuj earthquake. International Conference on Seismic Hazard with particular reference to Bhuj earthquake, New Delhi. Abstract Volume, 144-146.

Pande, P. (2007): A review of seismotectonics of Kutch rift basin (India) in light of Kutch earthquake-2001. Natural Hazards Spl. Vol. of IGC, 23-30.

Pande, P., Joshi, Y.C., Sharda, Y.P. and Joshi, K.C. (2003a): Isoseismal map and isoseist characteristics. P.Pande and J.R.Kayal (Eds.). Geol. Surv. India Special Publ. No. 76, 147-153.

Pande, P., Sharda, Y.P., Ghevaria, Z.G., John, B., Madhav, C. and Devrajan, M.K. (2003b): Secondary effects of the earthquake. P.Pande and J.R.Kayal (Eds.). Geol. Surv. India Special Publ. No. 76, 173-187.

Seed, R.B. (2002): Dams. 2001 Bhuj, India Earthquake Reconnaissance Report. S.K.Jain, W.R.Lettis, C.V.R.Murty and J.Bardet (Eds.). Earthquake Spectra, EERI Publ. No. 2002-1, 131-146.