DAMAGES OF SMALL TO MEDIUM SIZE EARTH DAMS DURING BHUJ EARTHQUAKE OF 26 JANUARY 2001

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ABSTRACT

The M7.7 2001 Bhuj earthquake caused severe damages to earthen dams and embankments, and geotechnical infrastructure facilities in the Kachchh region. Of the 19 small to medium size dams (10-25m high), 9 were severely damaged. Longitudinal cracks along the dam, deep-seated circular sliding of the slopes, subsidence of the crest, lateral spreading of adjoining ground due to liquefaction resulting in large lateral displacements in the dam body, and damage to the spillway segment, are some of the major observations. Liquefaction appears to be the major cause of these failures. Indian code provisions related to seismic design of geotechnical facilities are very primitive. The performance of the earth dams during this earthquake has necessitated an urgent re-look at these provisions. This paper discusses six of the severely damaged earthen dams and embankments, and analyses the causes.

Introduction

The magnitude 7.7 earthquake event on 26 January 2001 centered about 20 km North-West of Bhachau in the Kachchh region of Gujarat seriously affected the earthen dams, embankments and infrastructure utilities (communications, highways, railways and ports). There are about 19 small to medium size dams of 10 to 25 m high, in Kachchh district. Besides, there are many more smaller size dams also in this region. Nine dams have been reported very severely damaged. Most of the damaged dams are located in and around the meizoseismal area, and lie within 80 km radius from the epicenter. Dams located east of Bhuj town suffered the maximum. Over 10,000 km^2 in the Rann of Kachchh sustained massive liquefaction, which resulted in ground subsidence and spreading at several locations. The

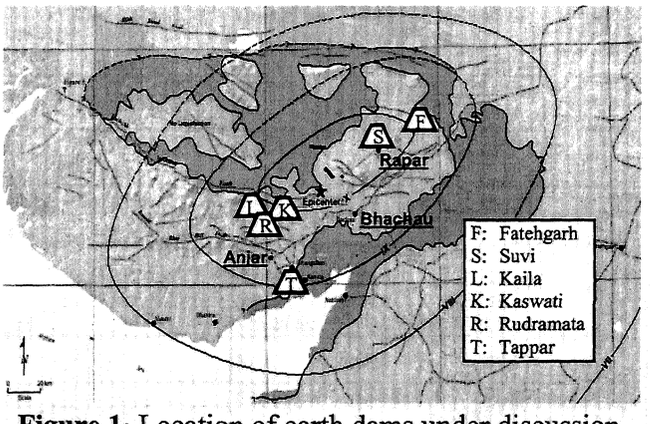

Figure 1: Location of earth dams under discussion. Isoseismals from Jain *et al*, 2001.

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consequent horizontal ground displacement resulted in longitudinal ground cracks at several locations. The details of the geological conditions leading to liquefiable topsoil conditions are described in detail elsewhere [Jain *et al*, 2001]. The authors visited six of these dams as part of the effort of the EERI Post-Earthquake Reconnaissance Team that surveyed the affected area. These dams are located at Fathegrah, Suvi, Kaila, Kashwati, Rudramata and Tappar (Figure 1). This paper presents the salient details of these dams, and discusses the seismic performance and an analysis of the possible causes behind the failure these dams.

Salient Details of the Six Dams

Table 1 gives details of the six dams; all six are earthen dams. As per the seismic zone map of India (IS:1893, 1984), these dams are located in zone V, the most severe one. Except for the Tappar dam, the rest are intended for irrigation purposes.

Table 1: Salient details of dams in the Kachchh district under discussion.

Item	Details	Earth Dam					
		Fatehgadh	**Suvi**	**Tappar**	**Kashwati**	**Rudramata**	**Kaila**
Location	Village Tahasil	Fatehgardh Rapad	Suvi Rapad	Anjar -	Lodal Bhuj	Nokhania Bhuj	Bhakhana Bhuj
General	Purpose	Irrigation	Irrigation	Water supply	Irrigation	Irrigation	Irrigation
	River	Malan	Suvi	Sakra	Kaswati	Khari	Kaila
	Area of catchment	104 km^2	161 km^2	303 km^2	67 km^2	572 km^2	178 km^2
	Mean annual rainfall in catchment		129.50 Mm^3				
	Mean annual rainfall	348 mm	358 mm	356 mm	350 mm	333 mm	335 mm
	Type	Earthen	Earthen	Earthen	Earthen	Earthen	Earthen
Cross-section	Bed rock	Lime stone, sandstone	Soft rock	Sand rock *(loosely commented medium sand)*	Sandstone, Shale	Sandstone	Sandstone, Shale
	Max. height above lowest point of foundation	11.20 m	15.00 m	16.00 m	16.15 m	27.37 m	23.46 m
	Length at top of Dam	14049 m	2097 m	4054 m	1455 m	875 m	1067 m
	Total Volume Content: Concrete Masonry Earthwork	 0.000785 Mm^3 - 0.57 Mm^3	 - - 0.26 Mm^3	 - - 1.319 Mm^3	 - 0.0046 Mm^3 -	 0.0029 Mm^3 0.02 Mm^3 0.85 Mm^3	 - - 0.43 Mm^3
Spillway	Type	Chute	Chute	Gated, Chute	Ground bar waste weir	Ogee	Ogee
	Length	35 m	122 m	160 m	175 m	436 m	213 m
	Energy dissipator	Stilling basin	Stilling basin		Stilling basin	Stilling basin	Stilling basin
	Maximum discharge	1246 m^3/s	990.50 m^3/s	2258 m^3/s	933.9 m^3/s	4055.39 m^3/s	1688.09 m^3/s
	Type, No., Size of Gate	Ungated	Ungated	14 (9014×4.57 m)	Ungated	Ungated	Ungated
Reservoir	Area at full reservoir level	5.29 km^2	4.40 km^2	11.45 km^2	1.95 km^2	8.20 km^2	2.32 km^2
	Gross storage capacity	7.45 Mm^3	14.28 Mm^3	48.82 Mm^3	8.88 Mm^3	64.74 Mm^3	14 Mm^3
	Effective storage capacity	14.63 Mm^3	11.90 Mm^3	13.64 Mm^3	8.23 Mm^3	55.70 Mm^3	-
	Area under submergence: Forest Waste land Culturable	 Nil Nil 10.16 ha	 Nil Nil 310.16 ha	 - - -	 NA NA 120.28 ha	 NA NA 102.48 ha	 NA NA 232.50 ha
	No. of villages under submergence	-	Nil	-	Nil	Nil	Nil
Canal	Length of canal	9.72 km	16.17 km	-	8.61 km	5.0 km	14.10 km
	Capacity (m^3/s)	0.90 : Left 0.19 : Right	1.586 : Left 0.524 : Right	- -	0.451 m^3/s	4.0 m^3/s	1.586 m^3/s
	Gross command area	1578 ha	4939.27 ha	-	2361 ha	5400 ha	4451.70 ha
	Culturable command area	919 ha	3192.30 ha	-	809 ha	4048 ha	3237.60 ha
	Villages under command: District Taluka Number of villages	 Kachchh Apar 6	 Kachchh Apar 6	 - - -	 Kachchh Bhuj 3	 Kachchh Bhuj 3	 Kachchh Bhuj, Nakhatrana 3, 1

Seismic Performance of the Dams

The locations of the six dams are shown in Figure 1 along with the isoseismals of the 2001 Bhuj earthquake. The dams were subjected to ground shaking of intensity IX or higher on the MSK Scale.

Fatehgarh Dam

This dam, located about 22km NE of Rapar and 60km NE of epicenter, sustained a shaking intensity of IX. The maximum height of the dam is about 11.2m from the lowest point of the foundation. The crest is about 3m wide and 4,049m long. The dam has an impervious core as seen in its cross-section (Figure 2); details of the cross-section are also given in Table 1. The dam sustained catastrophic failures of both upstream and downstream slopes. Longitudinal and transverse cracks were seen all along the crest and the upstream and downstream slopes.

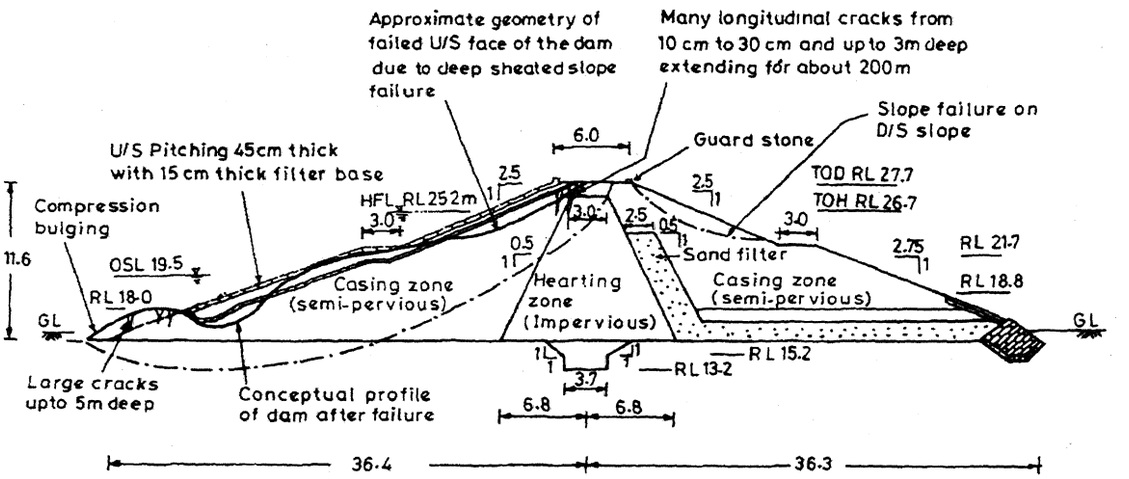

Figure 2: Cross-section of the earth dam at Fatehgarh in the Kachchh region.

Longitudinal cracks ranging from several centimeters wide to two meters are visible all along the crest of the dam (Figure 3). The entire crest dropped; the maximum crest settlement of about 30cm is noticed at location near to spillway (Figure 4). Transverse cracks with openings up to about 5cm are also observed near both the abutments. This could have been developed due to differential settlement of dam crest along the longitudinal direction. At two locations, a major deep-seated circular sliding of the slope, extending from the middle of crest to several meters beyond the toe of the dam has occurred. These slides seem to have occurred due to development of very high pore pressure and liquefaction of the foundation soil (Figure 5), which appears to be fully saturated due to lake water, which is almost at the toe of upstream slope. At several locations, ground spreading resulted in lateral displacement of the upstream toe. Typically, cracks up to 2m wide, over 2m deep extending over a stretch of 30-40m have been created at a few meters upslope from the toe (Figure 6). The compression toe bulging was also visible at or near the downstream toe of the dam.

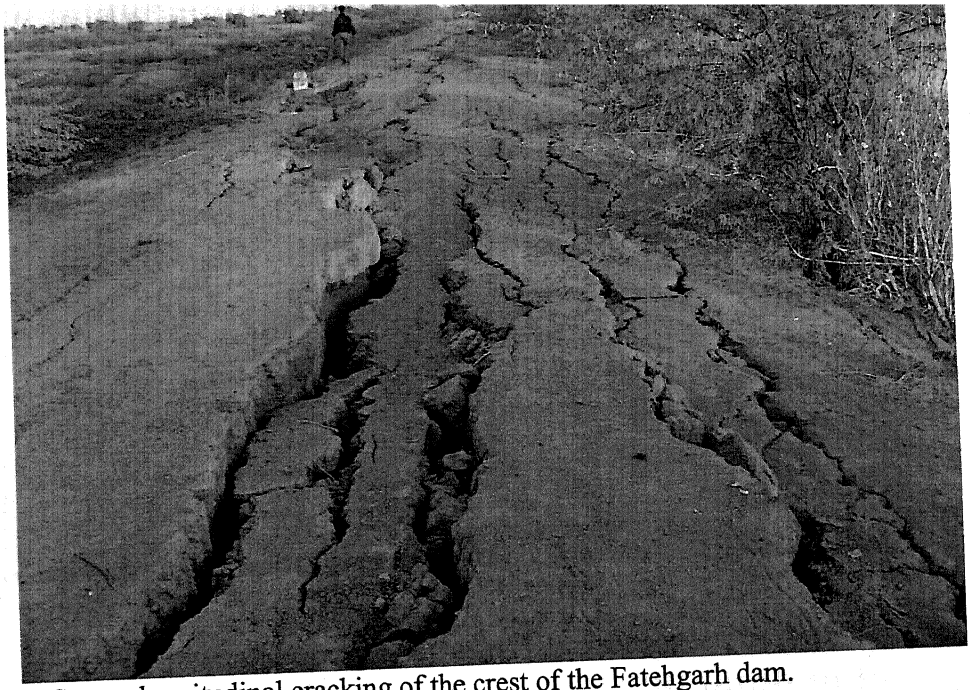

Figure 3 : Severe longitudinal cracking of the crest of the Fatehgarh dam.

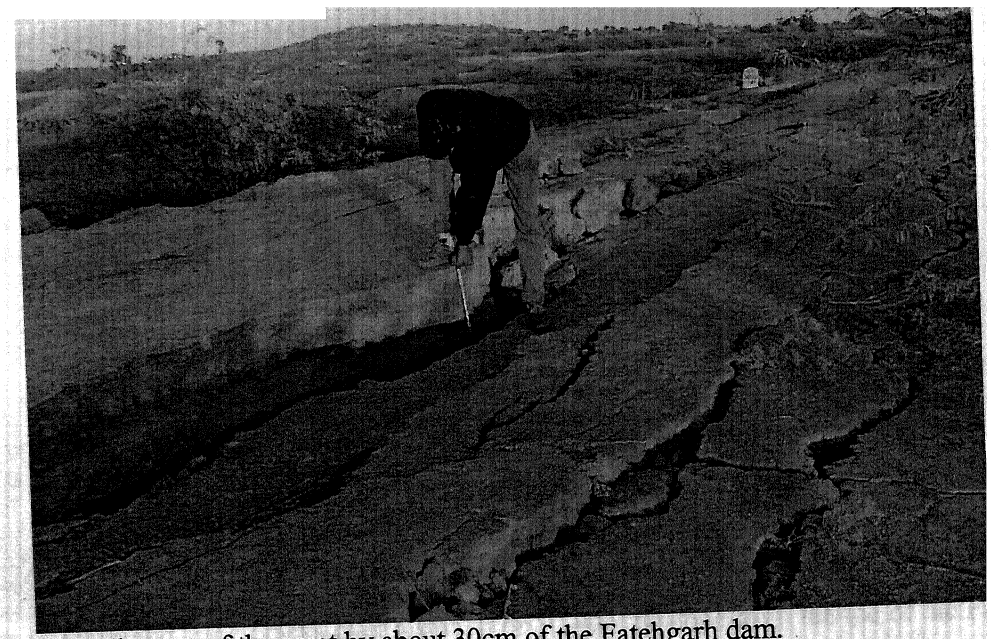

Figure 4 : Settlement of the crest by about 30cm of the Fatehgarh dam.

Figure 5: Liquefaction induced failure of the Fatehgarh dam.

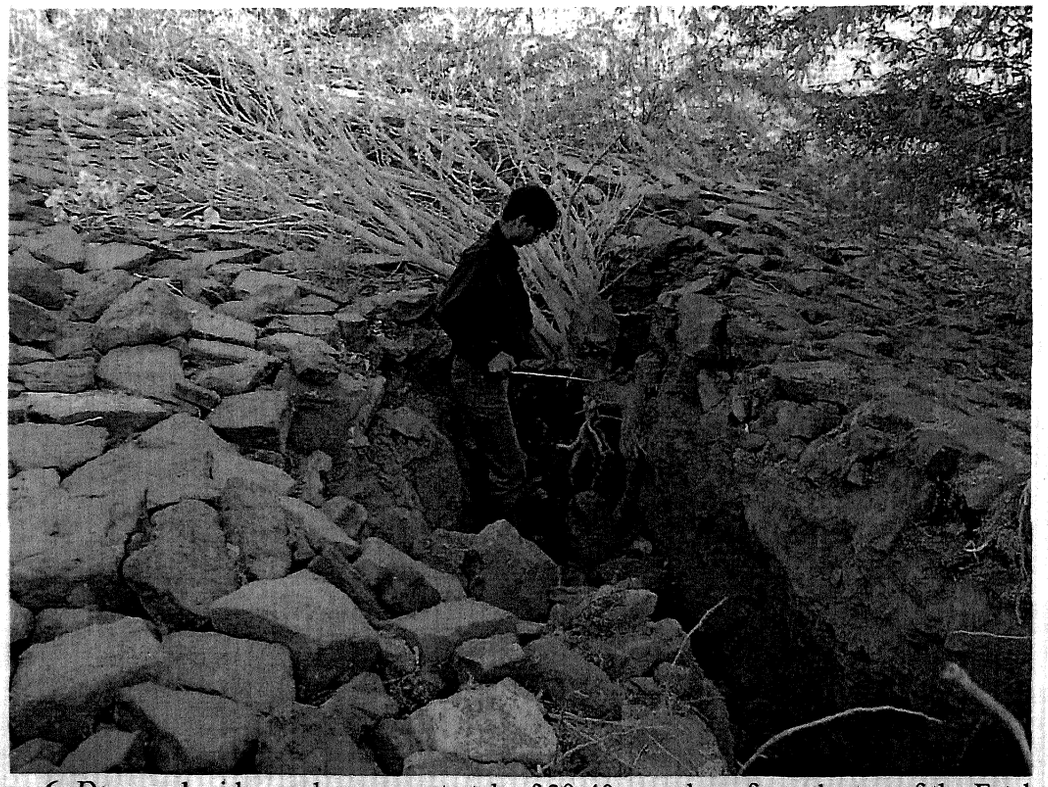

Figure 6: Deep and wide cracks over a stretch of 30-40m upslope from the toe of the Fatehgarh dam.

The failure is extended beyond the toe of the dam into the upstream ground resulting in the toe bulging, undulations and cracks. Scraps up to 1.5m high were seen with some evidence of rotational failure. A pillar located in the lake water about 2-3m from the upstream toe, was tilted inward, indicating the deep-seated failure condition. The subsoil at the site consists of sandy material. The liquefaction of the foundation soil was evident as sand boils and ground cracking were observed at the upstream toe location where major deep-seated failure of the dam has occurred.

Suvi Dam

The dam is located at about 17km NW of Rapar and about 33km NE of the epicenter, and sustained a shaking intensity of X. The maximum height of the dam is about 15m and the crest length is 2,097m (See Table 1). This dam has a poor construction history. Initially, the dam was constructed with masonry core with upstream and downstream shell of soil/boulders. Later, the crest of the dam was raised with pervious material without extending the core. A parapet wall was also constructed above the crest of the dam. The wall was not tied into the core. Severe longitudinal and transverse cracks appeared in this dam and several segments of the dam section collapsed. At many locations, both downstream and upstream slopes slid down. Several segments of the old rubble masonry core severely cracked and collapsed.

More than half the length of the parapet wall was collapsed. The main cause of the failure of this dam appears to be liquefaction of foundation soil, which has resulted in a subsidence up to a maximum of 60cm at the deepest section of the dam. The liquefaction of the foundation soil also caused lateral spreading near the upstream toe of the dam (Figure 7). A crack of about 100m long, 1m wide and 1.5m deep is visible at the toe of the dam.

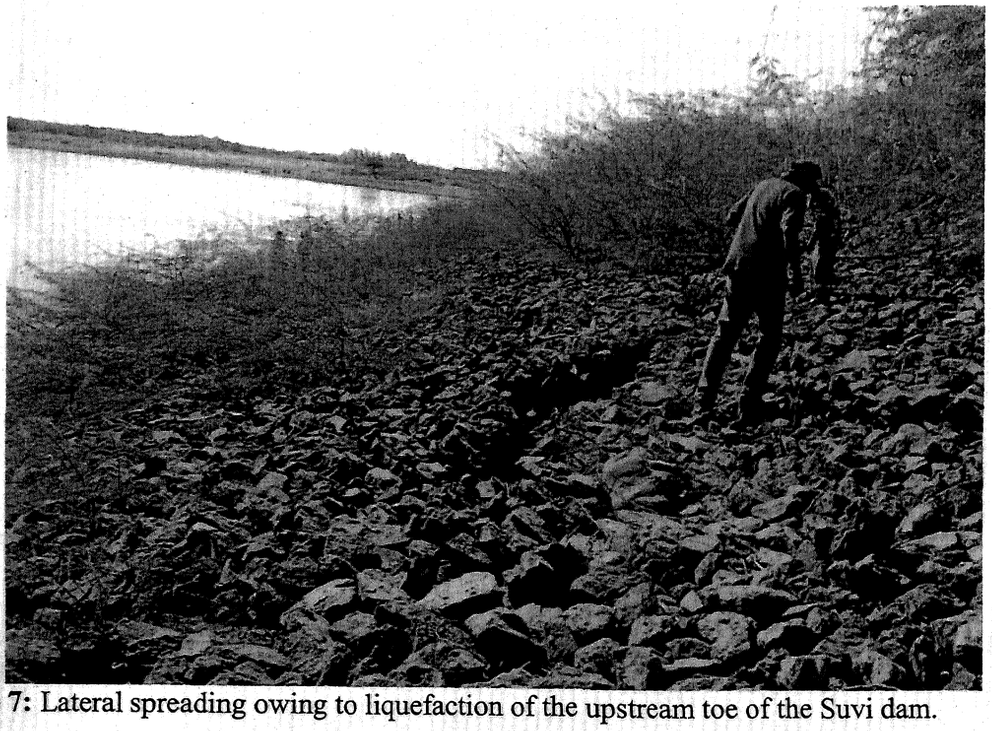

Figure 7: Lateral spreading owing to liquefaction of the upstream toe of the Suvi dam.

The Suvi Township located just downstream of the dam, was also severely hit by the earthquake. The water level in the dam was below the downstream toe when the earthquake occurred, otherwise the failure could have caused severe flooding of the village.

Tappar Dam

Tappar dam located at about 27km NE of Anjar district and 33km SW of epicenter, sustained an intensity of X. This is the most important dam of the region, supplying water to Gandhidham Township, Kandla Port and other neighboring regions. Originally, the maximum height of the dam was about 15m. Recently, the dam crest was raised by 3m using local soil. The present height of the dam is about 18m and the length of crest is 4,054m (See Table 1).

This dam experienced major upstream and downstream slope failures, and longitudinal cracks extending over a kilometer stretch of the crest. The cracks up to about 300m long, 1m wide and over 60cm deep were measured. The upstream berm has settled by over 8cm. The lateral spreading at the upstream toe caused several meter wide and over 2m deep lateral cracking, and the down drop of over 50m stretch of the upstream section (Figure 8). At several locations, the upstream section of the slope failed and scrap of the order of 75cm is seen. The water intake structure and the connecting pipelines are completely damaged. However, the newly constructed concrete spillway experienced only minor damage.

Figure 8: Lateral spreading near the upstream toe of the Tappar dam.

The major cause of the failure of the dam is due to extensive liquefaction of the foundation soil. Ejecta consisting of silty sandy soil at upstream toe and sand boils near the downstream toe of the dam were evident.

Kashwati Dam

Kashwati dam is located at about 35km NE of Bhuj and about 70km NW of epicenter, and sustained a shaking intensity of IX. This dam, used for irrigation purpose has a maximum height of about 16m and crest length of 1,455m (See Table 1). The dam consists of an impervious core and a shell of local sandy soils. The foundation soil appears to be sandy material. Abutments consist of highly weathered to weathered sandstone inter-bedded with shale.

This dam is severely damaged. A 10cm wide lateral crack extending for almost half a kilometer is visible at the crest. Massive upstream and downstream slope failures occurred at this dam site. Cracks up to 70cm wide and about 1m deep were observed on the upstream face of dam (Figure 9). Lateral spreading of about 1m wide and 1m deep is visible near the upstream toe. Also, toe bulging is evident. Liquefaction of the foundation soil appears to be the major cause of the dam failure.

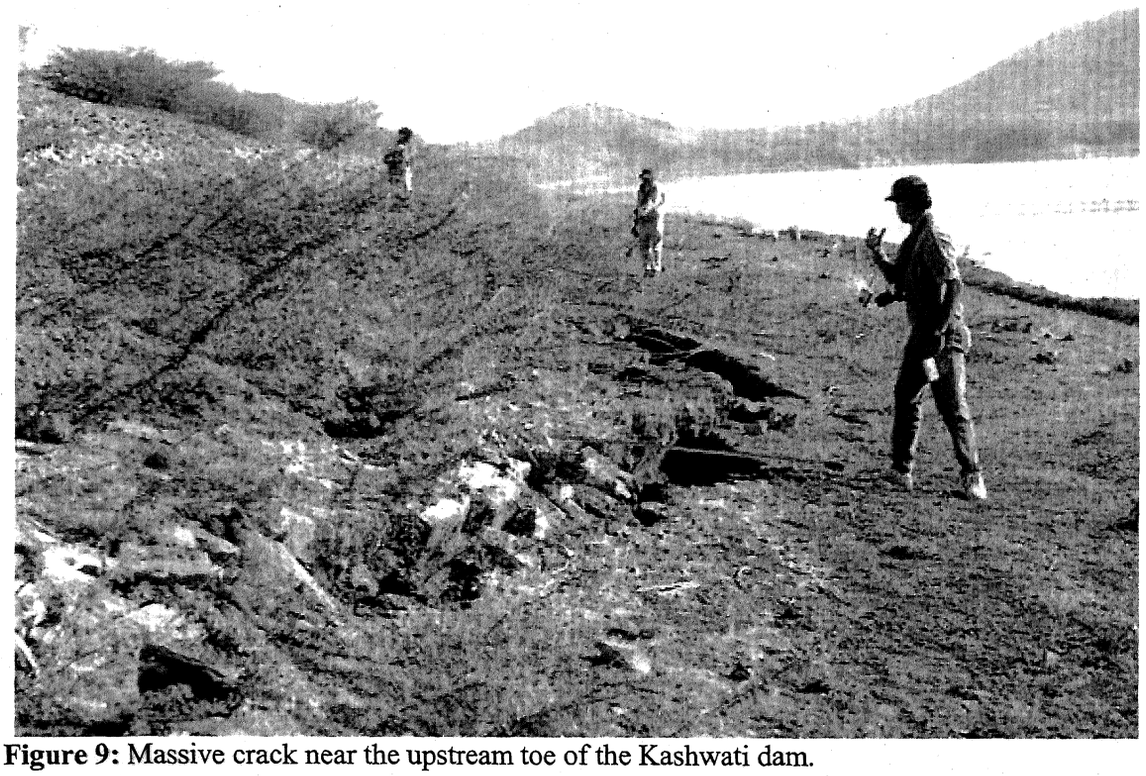

Figure 9: Massive crack near the upstream toe of the Kashwati dam.

Rudramata Dam

This dam is located at about 21km NE of Bhuj and about 85km NW of epicenter, and sustained a shaking intensity of IX. The dam is constructed at the confluence of Khari River, Pur River and an unknown creek, and is used for irrigation. The maximum height of the dam is about 27.4m and the crest length is 875m. The dam is constructed as a zoned dam consisting of semi-impervious material on the upstream side and of boulders on the downstream side (See Table 1).

The bedrock appears to be very close to the ground surface. About 6cm wide cracks are visible on both edges of the crest, which are developed due to sliding of both upstream and downstream slope of the dam. The downstream slope failure resulted in cracks up to 10cm wide and 150m long in a section of the dam. Also, a big depression of about 10m diameter is evident on the upstream slope. Cracking and slumping were observed along the upstream face and scraps of up to 1.5m high were noticed with some evidence of rotation and toe bulging. Reportedly, seepage at downstream toe was observed two days after the earthquake at locations corresponding to upstream slope failure. The liquefaction appears to be the major cause of the damage to this dam.

Some transverse cracks were visible near the water intake structure located in the vicinity of the east abutment (looking upstream), which is attributed to the differential settlement of the dam due to buried intake pipe structure and irregular abutment shape.

Kaila Dam

This dam is located at about 30km NW of Bhuj and about 95km NW of epicenter, and sustained a shaking intensity of IX. The dam consists of an impervious core and a shell of local soil (See Table 1). This dam experienced relatively minor damage. Longitudinal cracks were evident at the crest. Liquefaction of the foundation soil has caused lateral spreading near the upstream slope. Some cracks were evident in the Ogee shape concrete spillway and also in backfill of the spillway.

Summary

The Bhuj earthquake caused severe damages to 9 small to medium size earth dams located in the Kachchh district that lie within a radius of about 80km from the epicenter. The damages sustained include: (a) longitudinal cracks along the crest, toe, and upstream and downstream slopes, (b) deep-seated circular sliding of the slope extending from middle of crest to several meters beyond the toe of the dam, (c) subsidence of the crest of the dam, (d) lateral spreading of the ground due to liquefaction resulting in lateral displacement of the upstream toe, and displacement cracks up to 2m wide extending over a stretch of 30-40m a few meters upslope from the toe, and (e) cracks in the spillway and failure of the backfill behind the spillway.

At the time of the earthquake, the water in most of the dams was close to upstream toe. Except for the Rudramata dam, the rest of the dams seem to have failed due to liquefaction of the foundation soil beneath the upstream slope. Failures of downstream slope have also been recorded in most of these dams but the upstream slope failure was more severe compared to that in the downstream slope.

Concluding Remarks

The earthquake has exposed some basic inadequacies in the seismic design of the geotechnical facilities in India. An urgent effort is required to benchmark the extensive failures of earth dams with theoretical predictions using site-specific soil data. Also, the Indian Standards pertaining of seismic design of the various geotechnical facilities need to be comprehensively revised and necessary changes made.

Acknowledgements

The observations reported in this paper are part of the effort of the EERI Post-earthquake Reconnaissance Team. Numerous team members and other individuals organisations, particularly the engineers of the Department of Irrigation of the Government of Gujarat, contributed in direct and indirect ways. The study was made possible by generous grants from the EERI (USA) and the Department of Science and Technology, Government of India. The support of all these individuals and organisations is gratefully acknowledged.

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