Investigation of Liquefaction Failure in Earthen Dams during Bhuj Earthquake

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ABSTRACT

A Magnitude (M_W) 7.6 earthquake occurred in Bhuj, India on January 26, 2001. A large number of water-retaining earthen dams were affected by the earthquake. This paper examines the nature of distress in seven relatively severely affected dams. The consequences of these problems were not very severe because of the fact that (a) the reservoirs in question were almost empty at the time of the earthquake and (b) the dams performed reasonably in spite of being shaken by free-field horizontal peak ground acceleration (PGA) as high as 0.5g. Some of the distress reportedly was due to the liquefaction of saturated alluvium soil in foundation. Also analyzed herein three relatively large dams, each undergoing free-field ground motion with a PGA of 0.52. One of these dams, Chang Dam, underwent severe slumping, whereas Fatehgadh Dam and Kaswati Dam were affected less severely. The limited amount of subsurface information that is available indicates that the liquefaction within the top 2.0 to 2.5 m depth of foundation soils was relatively widespread underneath Chang Dam. For Fatehgadh Dam and Kaswati Dam, on the other hand, liquefaction occurred within the top 2.0 to 2.5 m depth of foundation soils near the toe, while the same layer underneath the dam crest may have liquefied only to a limited extent. This appears to be the explanation for the basic difference in the observed performance of Chang Dam and those of Fatehgadh Dam and Kaswati Dam. Results of sliding block analysis for these structures were also found to be in general agreement with the observed deformations.

INTRODUCTION

A Magnitude 7.6 (M_w 7.6) earthquake occurred in Gujarat state, India on 26 January 2001. The epicenter of the mainshock of the event was near Bachau at 23.36°N and 70.34°E with a focal depth of about 23.6 km. The event, commonly referred to as the Bhuj Earthquake, was among the most destructive earthquakes that affected India.

A large number of small-to moderate-size earthen dams and reservoirs, constructed to fulfill the water demand of the area, were affected by Bhuj Earthquake. Most of these dams are embankment dams constructed across discontinuous ephemeral streams. Although many of these dams were within 150 km of the epicenter (Figure 1), the consequences of the damage caused by the earthquake to these facilities were relatively light primarily because the reservoirs were nearly empty during the earthquake. Nature of damage to the embankment dams within the epicentral region is summarized in Table 1.

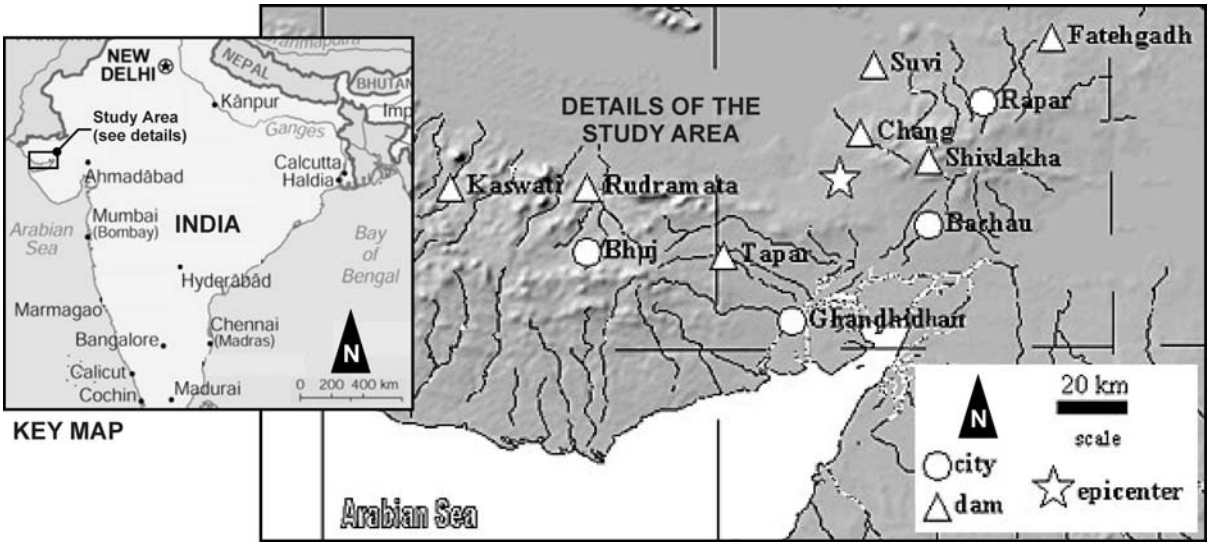

Figure 1. Study area

Performance of three such structures during Bhuj Earthquake has been examined here. Among these, Chang Dam was underwent almost a complete collapse mainly because of liquefaction of shallow foundation soils. Damage to Fatehgadh Dam and Kaswati Dam was relatively less severe. Direct evidence of liquefaction was not found near Fatehgadh Dam and Kaswati Dam. However, localized liquefaction of foundation soils was one of the causes of the observed post-earthquake distress within these dams.

OBSERVED DAM PERFORMANCE

A brief summary of the performance of the three dams is provided in the following subsections. For a more detailed account of the post-earthquake damage survey at dam sites reference may be made to the EERI (2001) Reconnaissance Report.

CHANG DAM

Chang Dam, constructed in 1959, is an earth dam with 15.5 m height at its maximum section and 370 m crest length (Figure 2). No site-specific information was available about the subsurface soils other than the qualitative information that the site is underlain by alluvial, loose to medium dense, sand-silt mixtures over shallow sandstone bedrock. Liquefaction susceptibility of the foundation soils was not considered in the original design.

Chang Reservoir was nearly empty at the time of Bhuj Earthquake. However the alluvium soils underneath the dam were possibly in a saturated state at that time. Bhuj Earthquake caused an almost complete collapse of the dam including damages to the impervious core and the masonry wall (Figures 2 and 3). Sand boils were observed near the upstream toe of Chang Dam following the earthquake. The deformation pattern is in fact indicative of a widespread liquefaction within the foundation soils.

Table 1. Observed Performance of Selected Dams

Dam	Crest Length, Height (m)	a_{max}	R (km)	Distress
Chang	370, 15.5	0.50g	13	Liquefaction in foundation, failure of upstream and downstream slopes, slumping, cracking
Fatehgadh	4049, 11.6	0.30g	80	Possible liquefaction in foundation near upstream toe, shallow failure in upstream slope, cracking
Kaswati	1455, 8.8	0.28g	110	Possible liquefaction in foundation near upstream toe, shallow failure in upstream slope, cracking, leakage
Rudramata	875, 27.4	0.30g	78	Possible liquefaction in foundation near upstream toe, shallow failure in upstream slope, cracking, leakage
Shivlakha	300, 18.0	0.50g	28	Possible liquefaction in foundation, upstream and downstream slope failure, cracking
Suvi	2097, 15.0	0.42g	37	Possible liquefaction in foundation near upstream toe, shallow failure in upstream slope, cracking
Tapar	4054, 13.5	0.41g	43	Liquefaction in foundation near upstream toe, shallow failure in upstream slope, cracking

Notes. 1. Estimates for a_{max} are based on Singh *et al.* (2003) attenuation relationship and Idriss (1990) site amplification relationship.
2. R is the approximate epicentral distance.

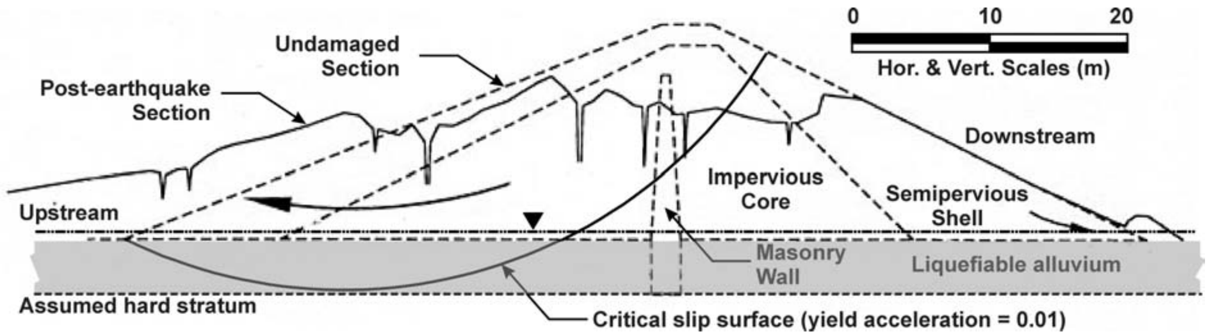

Figure 2. Cross-section of Chang Dam (modified from EERI 2001)

FATEHGADH DAM

Fatehgadh Dam, constructed in 1979, is an earth dam with a maximum height of 11.6 m and crest length of 4050 m (Figure 4). Like Chang Dam, Fatehgadh Dam is also underlain by loose to medium dense silt sand mixtures. Limited amount of subsurface exploration data indicate that the site is underlain by 2 to 5 m thick granular soils characterized with an SPT blow count between 13 and 19 (Krinitzsky and Hynes 2002).

Fatehgadh Reservoir was nearly empty during Bhuj Earthquake. However the alluvium soils underneath the upstresm portion of the dam was saturated at that time. Bhuj Earthquake triggered failure near the bottom portion of upstream slope (EERI 2001) possibly because of localized liquefaction near the upstream toe of the dam. The EERI (2001) also found cracks as deep as 1.5 to 1.7 m within the upstream portion of the dam (Figure 5) and instability near the top portion of the downstream slope following the earthquake. The problem of appearance of longitudinal cracks may indirectly relate to liquefaction of foundation soils. However, instability of the upper portion of the downstream slope may not be due to the liquefaction of foundation soils. The deformed shape of the dam section is presented in Figure 4 together with its pre-earthquake configuration for comparison.

Figure 3. Failed upstream slope of Chang Dam (courtesy EERI 2001)

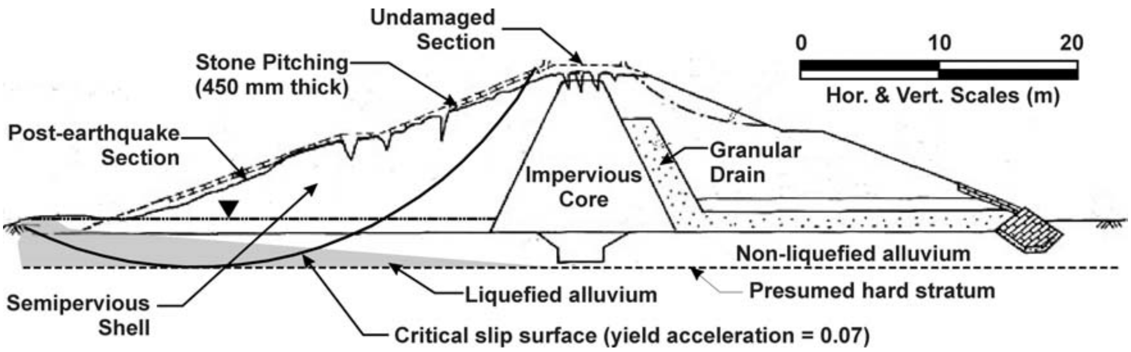

Figure 4. Cross-section of Fatehgadh Dam (modified from EERI 2001)

KASWATI DAM

Kaswati Dam, constructed in 1973, is an earth dam with a maximum height of 8.8 m and crest length of 1455 m (Figure 6). The dam is underlain by loose to medium-dense, alluvial, silt-sand mixtures. Limited amount of subsurface exploration data indicate that the site is underlain by 2 to 5 m thick granular soils characterized with an SPT blow count between 13 and 19, below which relatively dense granular soils with an SPT blow count typically above 25 is found (Krinitzsky and Hynes 2002).

Like the other impoundments, Kaswati Reservoir was nearly empty during Bhuj Earthquake. However the alluvium soils underneath the upstream portion of the dam was saturated during the earthquake. Bhuj Earthquake triggered shallow sliding near the bottom portion of upstream slope, and bulging of ground surface near the upstream toe (Figure 7a). Such distress may have been due to localized liquefaction near the upstream toe of the dam. EERI (2001) also report relatively narrow, longitudinal cracks along the crest of the dam running the length of the dam over which the lower portion of the upstream slope exhibited distress (Figure 7b). It appears that the problem of development of longitudinal cracks along the crest was indirectly due to localized liquefaction of upstream foundation soils. The downstream slope, on the other hand, remained largely unaffected. The deformed dam section is presented in Figure 6 together with its pre-earthquake configuration for comparison.

Figure 5. Open Fissures on the upstream face of Fatehgadh Dam (courtesy EERI 2001)

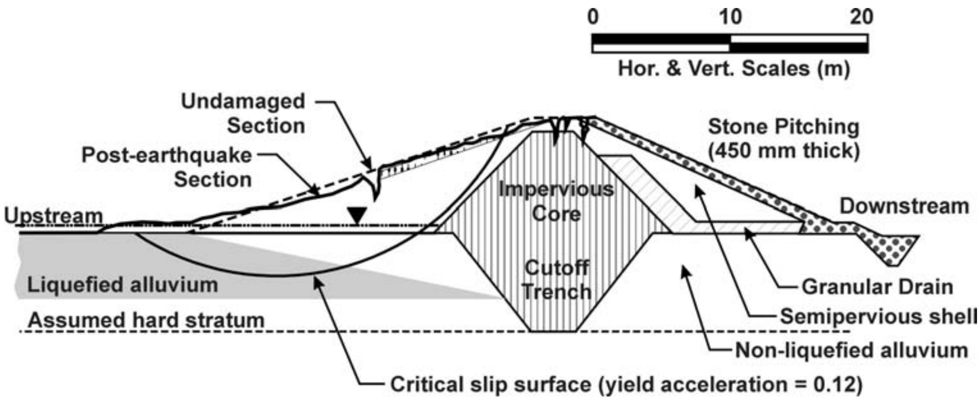

Figure 6. Cross-section of Kaswati Dam (modified from EERI 2001)

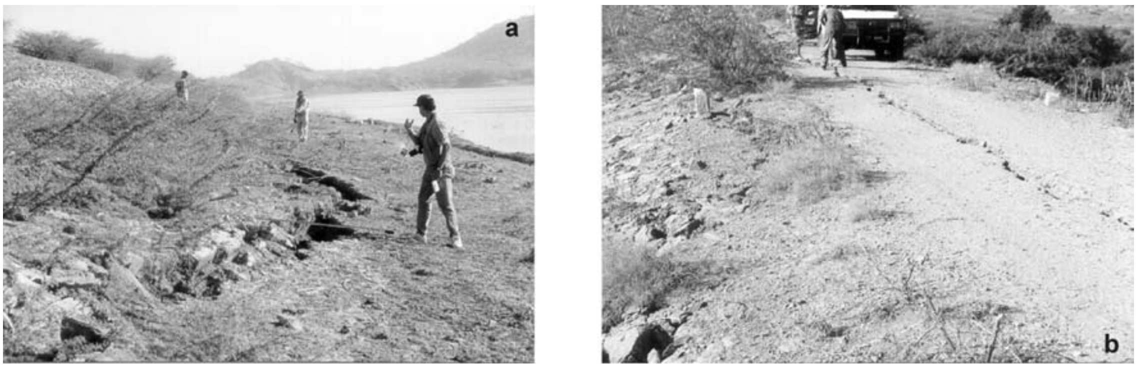

Figure 7. Kaswati Dam photographs: (a) Toe bulging and (b) Cracking of dam crest

SLIDING BLOCK ANALYSES

A simple seismic dam safety analysis is essentially a two-step procedure. In the first step, the liquefaction potential of the foundation soils and dam body is assessed and representative values of material shear strength parameters are estimated. In the second step, the deformation potential is assessed using appropriate values of material strength and earthquake load.

ASSESSMENT OF LIQUEFACTION POTENTIAL

The procedure for assessing liquefaction potential typically uses the Cyclic Resistance Ratio (*CRR*) as a measure of the liquefaction resistance of soils and the Critical Stress Ratio (*CSR*) as a measure of earthquake load. For cohesionless soils, *CRR* has been related to normalized SPT blow count, $(N_1)_{60}$, through correlations that depend on the fines content of the soil from field performance observations from past earthquakes (*e.g.*, Figure 8). The normalized SPT blow count is given by:

$$(N_1)_{60} = N \times \left(P_a / \sigma'_{v0}\right)^{0.5} \times ER \qquad (1)$$

where N is the raw SPT blow count, P_a is the atmospheric pressure (≈ 100 kPa), σ'_{v0} is the effective vertical stress at the depth of testing, and ER is the energy ratio (≈ 0.92 in a typical Indian SPT setup).

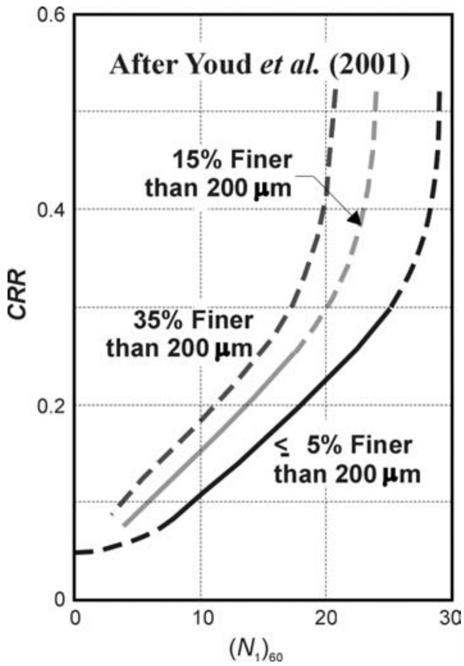

Figure 8. *CRR* - $(N_1)_{60}$ Correlations (from Youd *et al.* 2001)

Available SPT data from Fatehgadh Dam and Kaswati Dam however indicates that the shallow foundation soils underneath the dam body were characterized with a blow count between 13 and 19. For assessing liquefaction potential of foundation soils we assumed that the fines content of these shallow alluvium layers were 15% or less.

The procedure for assessing liquefaction potential uses the Critical Stress Ratio (*CSR*) as the measure for earthquake load, where

$$CSR = 0.65 \times \left(a_{\max} / g\right) \times \left(\sigma_{v0} / \sigma'_{v0}\right) \times r_d \times K_m^{-1} \times K_\alpha^{-1} \times K_\sigma^{-1} \qquad (2)$$

where a_{max} is the peak ground acceleration, g is the acceleration due to gravity, σ_{v0} is the total vertical stress, r_d is a correction factor to account for the flexibility of the soil column, and K_m, K_α and K_σ are correction factors to account for the Magnitude of the earthquake, the presence of initial static shear (*i.e.*, whether the layers are in a slope) and the depth of the layer (*i.e.*, the level of initial overburden pressure), respectively. We estimated the value of r_d for a given depth from Seed *et al.* (2003) median relationship. Correction factors K_m, K_α and

K_σ were obtained from the relationships recommended by Youd *et al.* (2001) using estimates of relative density obtained from (Olson and Stark 2003[b]):

$$D_r = \sqrt{(N_1)_{60}/44} \tag{3}$$

The results of assessment of liquefaction susceptibility of the foundation soils underneath Chang Dam, Fatehgadh Dam and Kaswati Dam are presented in Table 2. These results indicate that, if saturated, the foundation soils are susceptible to liquefaction for the estimated horizontal peak ground accelerations at dam sites (see Table 1 for a listing) under free-field conditions.

Table 2. Liquefaction susceptibility of foundation soils

Dam	*CRR*		*CSR*		Liquefaction susceptibility	
	Crest	Toe	Crest	Toe	Crest	Upstream Toe
Chang	0.34	0.34	0.36	0.75	Yes	Yes
Fatehgadh	0.34	0.34	0.18	0.36	No	Yes
Kaswati	0.34	0.34	0.15	0.36	No	Yes

Shallow foundation soils underneath the upstream slopes of all the three dams were below water levels observed during the earthquake. Therefore these soils were saturated and susceptible to liquefaction. Observed deformation pattern of Chang Dam also makes it apparent that shallow foundation soils near the downstream toe were also saturated during the earthquake possibly because of seepage through masonry cutoff wall. Shallow foundation soils near the downstream toes of Fatehgadh Dam and Kaswati Dam were however partially saturated.

As a result, liquefaction may have been triggered underneath the entire section of Chang Dam, while liquefaction underneath Fatehgadh Dam and Kaswati Dam was relatively localized and was triggered only underneath the upstream slopes. Inferred extent of liquefied soils underneath Chang Dam, Fatehgadh Dam and Kaswati Dam are shown on Figures 2, 4 and 6, respectively.

The semi-pervious shell, and impervious core of the multi-zone earth dams studied in this research are compacted, cohesive and partially saturated. The drainage filter is non-cohesive but partially saturated. Such soils were therefore not considered liquefiable.

DEFORMATION ESTIMATION

Dam sections shown on Figures 2, 4 and 6 were analyzed to estimate the yield accelerations. Computer program XSTABL Version 5.2 (Interactive Software Designs, Inc., 1994) and Modified Bishop method was used in the undrained, limit-equilibrium slope stability assessment. The input parameters used in the analyses are listed in Table 3. For the semi-pervious shell within dam body, these parameters reflect typical shear strengths. The strength parameters of the liquefied and non-liquefied portions of the foundation alluvium layers were obtained from Olson and Stark (2003[a]). The critical failure surfaces obtained from these analyses superposed on Figures 2, 4 and 6. These failure surfaces are in agreement with the observed patterns of distress.

The yield accelerations obtained from the undrained, limit-equilibrium slope stability assessment are shown on Figures 2, 4 and 6 and listed in Table 4. Estimates of deformation for these values of yield acceleration were obtained using the upper-bound relationship proposed by Hynes-Griffin and Franklin (1984). These estimates of deformation magnitudes are also presented in Table 4 together with observed deformation magnitudes. From Table 4 it appears that the estimated deformations are in reasonable agreement with observations.

Table 3. Soil properties in undrained limit equilibrium stability assessment

Dam	Soil Unit	Unit weight (kN/m^3)	Cohesion (kPa)	ϕ	s_u/σ'_v
Chang	Semi-pervious shell	18	22	30.5°	
	Impervious core	20	50	0.0	
	Masonry wall	22	100	0.0	
	Liquefied foundation soil	18	0.0		0.209
	Non-liquefied foundation soil	18	0.0		0.411
	Deep alluvium	20	0.0	41.5°	
Fatehgadh	Semi-pervious shell	18	9.4	30.5°	
	Impervious core	20	50	0.0	
	Liquefied foundation soil	18	0.0		0.209
	Non-liquefied foundation soil	18	0.0		0.411
	Deep alluvium	20	0.0	41.5°	
Kaswati	Semi-pervious shell	18	9.4	30.5°	
	Impervious core	20	50	0.0	
	Liquefied foundation soil	18	0.0		0.209
	Non-liquefied foundation soil	18	0.0		0.411
	Deep alluvium	20	0.0	41.5°	

Table 4. Yield accelerations, and estimated and observed displacements

Dam	Yield Acceleration	Estimated Displacement	Observed Horizontal Displacement
Chang	0.01*g*	> 8 m	7.1 m
Fatehgadh	0.071*g*	0.70 m	0.60 m
Kaswati	0.12*g*	0.32 m	0.60 m

CONCLUSIONS

Damaging effects of Bhuj Earthquake on embankment dams have been considered in this paper with particular reference to Chang Dam, Fatehgadh Dam and Kaswati Dam. Liquefaction to various extents of the foundation soils underneath these embankment dams during Bhuj Earthquake have been reported as one of the major causes of the distress within these dams. The data presented in this paper indicate that liquefaction within the shallow foundation soils would have been widespread underneath Chang Dam, while that underneath Fatehgadh Dam and Kaswati Dam were relatively localized. This assessment is in qualitative agreement with the facts that the damage to Chang Dam was near total, while those inflicted on the other two dams were relatively less pronounced. The sliding block method was then used to estimate the magnitude of observed deformations. This exercise indicates that the inferred failure pattern and magnitudes of deformation for the three dams are in reasonable agreement with observations.

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