8. Damage to Civil Structures and Liquefaction

M. Hamada, O. Aydan and J. Kiyono

8.1 Dams

Most of the dams are earthen dams except a few, which is stone masonry, built. The dams are built for irrigation purposes. There are more than 174 earth dams in the region. Seven medium sized dams and 14 small sized dams in Kutch were damaged. The major dams, which were damaged during the earthquake, were Chang, Tapar, Suvi, Shiviakha, Kaswati and Rudramata dams. Most of the dams failed or damaged at their old river course sections. The reason of the failure or damage was associated with the liquefaction of sub-soil below the embankment of the dam. Photo 8.1 shows views of damage to Suvi and Chang dams.

8.2 Port Facilities

The Kandla Port was built in 1955. No crane is toppled. The Port Building on the piles near the main gate tilted with an inclination of 1-2 degree. The Kandla port is aligned in the direction of NS.

(a) Chang Dam

[b] Suvi Dam

Photo 8.1. Views of Failures

(a) chipped pile head

(a) hair cracks on the pile surface

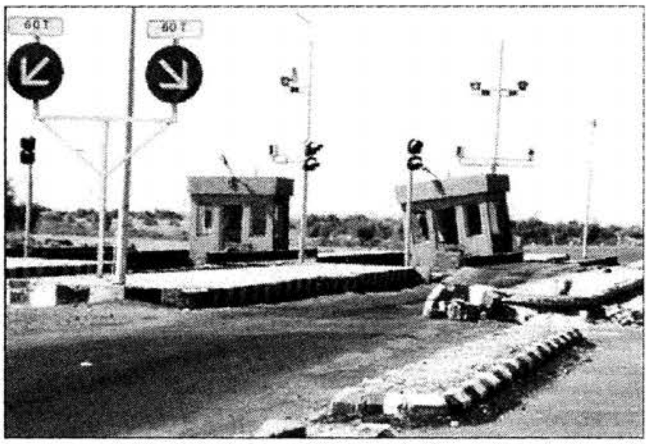
Photo 8.2. Cracking of piles at Kandla port

Photo 8.3. A view of damaged oil jetty at the Kandla port on March 19, 2001.

(a) Bachau-Bhuj roadway

(b) roadway to Manfera

Photo 8.4. Damaged roadways due to ground deformation



(a) toll gates

(b) bridge embankment

Photo 8.5. Damage to toll gates and settlement of bridge embankments

Berths No.1 to 5 at Kandla Port have developed some major structural damage. Berths No.6 to 9 are functional. The strong shaking damaged many piles supporting the docks of berths No.1 to No.5. The piles were cracked by the bending, and some concrete pieces were chipped from the pile tops. The pile length is about 20m below the frame structure and the diameter is 60cm. The cracks on the piles are not severe as shown in Photo 8.2. However, they have to be repaired with the steel plate or carbon fiber jacketing in order to protect the steel bars from the corrosion.

The old jetty of the port on the piles with a length of 15m is shifted towards the sea. The top of piles had small hair cracks. Furthermore, the settlement of filled section of the port was about 7cm. The jetty of the oil-pipelines at Kandla port was heavily damaged due to breakage of the piers (Photo 8.3). The piers were almost ruptured at their mid.

8.3 Transportation Facilities

Damages to railways can be classified as follows: damage to railway tracks, signal and telecommunication system, electrical facilities, stations and bridges. Damage to railway tracks was observed in the form of bending and distortion of rails and tracks due to ground shaking and deformation. This situation could be clearly observed at Gandhidham railway station. There were three railway lines. Two of them were under construction. It was apparent that some rails were bent or were offset although they were repaired after the earthquake. 20 railway stations across Kutch were damaged as a result of the earthquake. Gandhidham station was the worst hit. Gandhidham railway station was an RC structure and some structural damage to the railway station was observed. It was also reported that an accident took place on the railway due to de-railment of a train at Ratnal.

Photo 8.6. Gap between foundation and surrounding soil at Rudramata bridge

Out of 650km of highways, 100km severely damaged. Most of roadways had to be re-surfaced due to extensional and bulging type cracking (Photo 8.4). In some places, the traffic had to be diverted for the repairment of embankments. The tollgate buildings of the highway 8A were broken at their base columns (Photo 8.5). Furthermore, the embankments of bridges settled and caused the slow down of the traffic (Photo 8.5).

Railway bridges were almost non-damaged. At a railway bridge 7km from Halvad (100km from the USGS epicenter) there was no visible damage while some damage to roadway bridges at the same location was observed. The only reported damage occurred at Bridge No.48 between Kukma and Bhuj and it was restored on 3rd Feb., 2001.

Most of the minor/major roadway and highway bridges in Kutch region were damaged. Parapets of the minor and major bridges were totally or partially toppled or displaced in the entire region affected by the earthquake. The settlement and lateral spreading of ground particularly affected the piers of Hadakia Bridge and Rudramata Bridge (Photo 8.6). The soil at both sides of the bridge abutments settled and spread

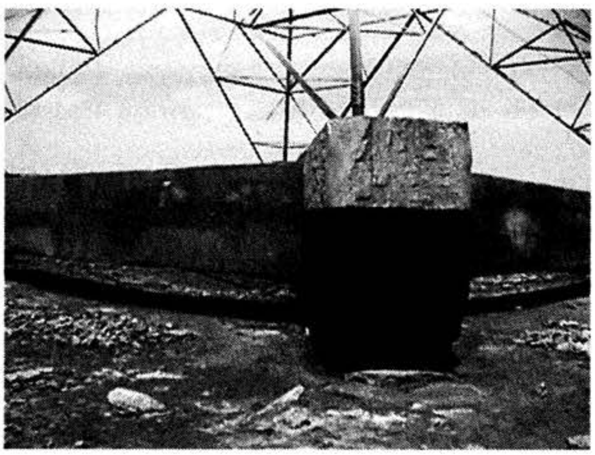


Photo 8.7. Damaged pylons near Hadakia Bridge

towards the center of the valley.

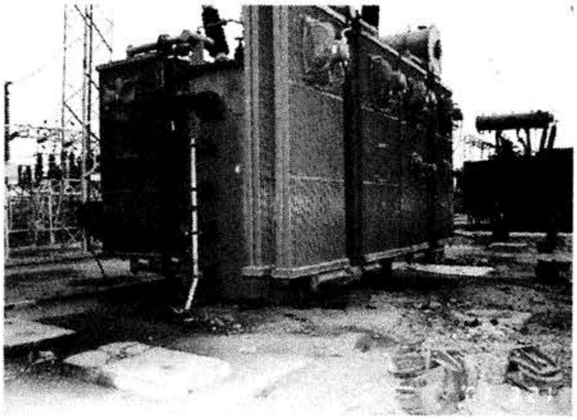
8.4 Industrial Facilities

(1) Electricity and Power Plants

There are three thermal power plants, namely, Panandro TPP, Ahmebabad TPP and Mahesana TPP. These thermal power plants burn lignite and they were non-damaged during the earthquake. The earthquake led to a tripping of various power plants including the 1200MW Wanakbori, 450MW Gandhinagar, 280MW Dhuvaran, 111MW Panandro, 11.0MW Sikka, 90MW Gandhar and 380MW AECO plants, resulting in a total generation loss of 2600MW.

The 370MW lignite (coal) burning plants located in Panandhro about 180km northwest of the epicenter and they experienced only minor cracking. The supply is supplemented by a coal-burning plant in Ahmedabad, 211km east of the epicenter. In Gujarat State, the Kakrapar nuclear power plants Unit No.1 (220MW) and No.2 were in operation at the time of the earthquake, which was located about 400km southeast of the epicenters. The Kakrapar nuclear power plant suffered no damaged and it did not stop supplying power just after earthquake.

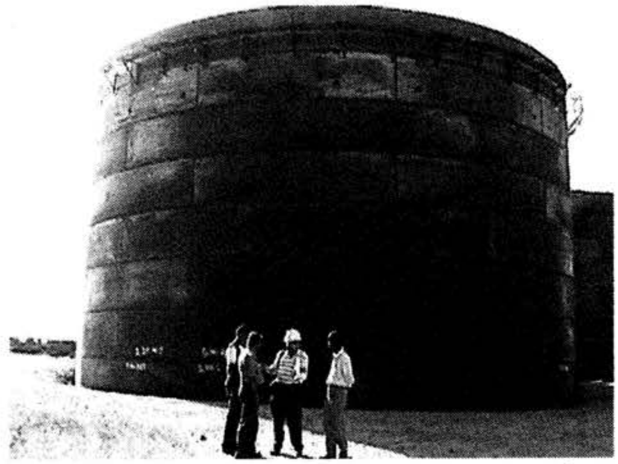
The Gujarat Electricity Board is supplying power to all the town and villages through a network of 3, 2 and 40 number of 220kV, 132kV, 66kV sub-stations respectively and by 225 number of 11kV feeders. Three 220kV sub-stations are located in Anjar, Nanikhakhar and Nakhatrana. One 132KV sub-station is located at Samakhiyali. The electricty of Indian System is as follows: 400kV → 220kV → 132 kV → 66kV → 11kV → 440V → 220V. Frequency is 50Hz. Power is transmitted from Panandhro, through 220kV and 132kV systems, southeast through the region. Over a dozen substation control buildings collapsed, and a total of 45 were damaged. The control building damage had the greatest impact on the overall system failure. Pylons were almost non-damaged in the earthquake area even some of them passed through the marsh lands and salt playas. but some of them passes through salt playas experienced some damages. Photo 8.7 shows the damage of the pylon foundation in salt playas near Hadakia Bridge. The foundation moved and about 11 cm wide gaps occurred between the pile-foundations and the surrounding ground, and the concrete beams which connected the pile foundations experienced some cracks.



(a) derailed transformer

(b) damaged circuit breaker

Photo 8.8. Damaged transformers and breakers at Anjar substation



(a) tilted tank

(b) damaged tank

Photo 8.9. Tilted and damaged tanks at the Friends Tank Farm

In the Anjar 220kV substation, the communications system and power protection system had failed when the battery rack collapsed. They could not enter the control building because of concerns about collapse of the roof. The unanchored control panels inside did not topple. In the yard, all transformers derailed, some bushings broke (Photo 8.8). Four circuit breakers had failed porcelain insulators (Photo 8.8). The first major substation was brought back online on 1/29 in Bhuj (132 kV), and the first 220 kV substation brought back on line in Anjar on 1/30. As of 2/5, an estimated 80% of the region's power had been restored.

(2) Oil Tanks

Tanks at Friends Tank Firm, Oil India and Trisuns Chemical Plant were checked. There are 66 cylindrical tanks having a diameter ranging between 7-26m at Friends Tank Farm. The pump houses were RC type and had structural damage. No damage to pumps was reported. The tank yard is built on a reclaimed land. The topsoil was excavated to a depth of 2m after constructing an all-around wall and drained. Then lateritic soil with poor grading was filled to a height of 3.5m. After compaction, tanks were built over this soil basement.

Two tanks were heavily tilted and connections of valves to pipelines were

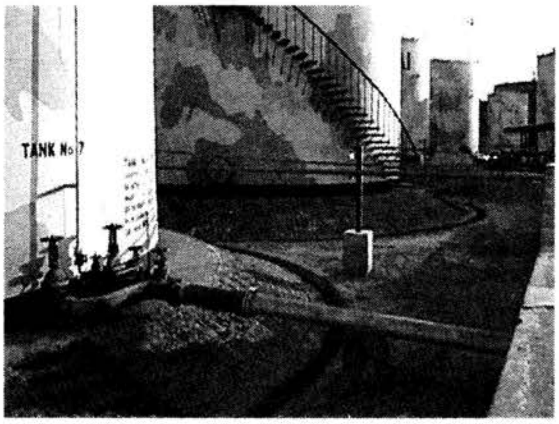


Photo 8.10. Damaged Tanks at Oil India

(a) broken fixtures

(b) liquefaction at pipeline base

(c) damaged pipelines with collapsed steel frame

Photo 8.11. Damage to pipelines

damaged due to tilting and sinking of the tanks (Photo 8.9). It seems that the tilting and sinking were due to foundation failure associated with the base soil. Considering the bulging and motion of the ground, it seems that the ground moved in the direction of S40W-S50W. Besides the two heavily tilted tanks, some differential settlements, tilting and sinking of the tanks were observed in the newly reclaimed tank yard. In oil tank yard, which was built for more than 20 years ago, the settlement of the ground was not observed.

Most of tanks were non-damaged in the Tank farm of Oil India (Photo 8.10). Nevertheless, some oil tanks were buckled or tilted. Some of damage to tanks was due to the liquefaction of the foundation soil. There were 6 steel tanks with a conical fixed roof. No damage to tanks was observed although it was very close to the epicenter of the earthquake. The tanks had 2m thick concrete basement. The buildings in this complex, however, were heavily damaged. One of storehouses was completely collapsed while the roofs of other storehouses were partially collapsed.

(3) Pipelines

Product pipelines from Vadinar to Kandla & Kandla to Bhatinda were shutdown. The pipe racks made of steel and were bent or buckled in the vicinity of the port. There was no breakage of the pipelines at any location although they were displaced from their original locations. The steel stripe

(a) Dhori

(b) Hadakia Bridge

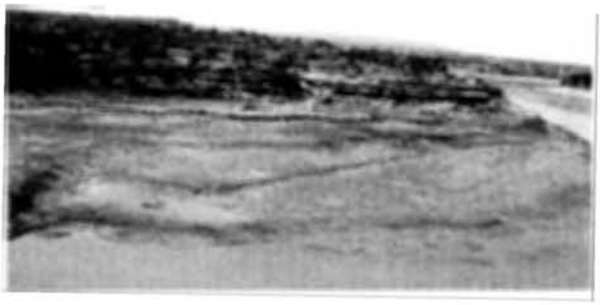
Photo 8.12. Some examples of liquefaction

type fixtures were either broken or separated from their welding locations (Photo 8.11(a)). The pipes were displaced both laterally 30cm and longitudinally 40cm. The direction of movement was NE towards the epicenter. The liquefaction and lateral movement of the ground was observed at the base of pipelines as shown in Photo 8.11(b). Crude oil pipelines from Salaya, feeding Koyali/Mathura/Panipat refineries resumed operations since 27th Jan after due checking. The oil pipelines from the Kandla Port were severely damaged (Photo 8.11(c)). The pipelines are supported by the two layer steel frames and each frame supports three pipelines. Two of them were filled with oil during earthquake. The pipelines are running to the NS direction and the south ends are curved to the west direction. Because the ground motion of the NS direction was dominant and the shaking modes were different for the three parallel pipelines, which have different curvatures, the steel frames were buckled and collapsed with the pipelines.

8.5 Liquefaction and Lateral Spreading

Widespread liquefaction was observed in the Rann of Kutch, the Little Rann of Kutch as well as the coastal areas of the Gulf in the vicinity of Ghandidham, Kandla, and between Malya and Samakhiali. Liquefaction was widespread particularly along the seashore, riverbeds, ponds and marshland and salt playas. The liquefaction has manifested along long fissures and at many places it is of vent type (Photo 8.12(a)). This phenomenon was responsible for failure of some embankments in the mesoseismal area. In the coastal areas and dam reservoirs evidences of lateral spreading were also observed. Some embankment failures and traces of liquefaction and lateral spreading of ground were observed at distances more than 100km from the epicenter such as nearby the Bridge over Malia Creek and Kadhan in Pakistan. The bridge was severely damaged due to the liquefaction and its induced ground displacement. Numerous sand vents could be observed on the river bed in the neighborhood of the bridge as shown in Photo 8.12(b). The evidences of liquefaction-induced ground displacement were found on the riverbed. And the concrete piers with caisson foundations moved toward the river center due to the ground displacement as shown. The bridge

(a) sand boiling



(a) wide spread lateral spreading

(b) lateral spreading around reservoir

(b) crack due to lateral spreading

Photo 8.13. Liquefaction and lateral spreading at Chang dam

Photo 8.14. Settlement and lateral spreading in the vicinity of Rudramata Bridge

also suffered considerable subsidence of foundations caused by liquefaction and the transportation function was lost after the earthquake.

Some lateral spreading of ground was observed within the Suvi dam reservoir. This may be due to soil liquefaction as quartzitic sand with a repose angle of 32 degree is observed along the cracks. The slumped section of this dam was also thought to be the result of liquefaction of soil at the base of the dam.

Although the base rock of the Chang dam was mudstone with almost horizontal layering, the old river course may be consisted of sandy material. In the upstream side the sand boiling can be clearly observed even more than 50 days passed over the earthquake (Photo 8.13(a)). It seems that the failure of the dam is due to liquefaction at its base and it resembles to the failure of San Fernandes dam. Furthermore, some lateral spreading could be observed at many locations around the reservoir (Photo 8.13(b)).

Liquefaction observed within the Kandla port and its vicinity. Although the effect of liquefaction on port facilities was quite small, there were several examples of liquefaction. Liquefaction was also observed at Navlakhi port in the Kathiawar peninsula and Advani port in Mundra along the coast of Arabian Sea.

Wide spread lateral spreading of ground was observed at both sides of the valley of the Rudramata Bridge as shown in Photo 8.14(a). The soil at both sides of the settled and spread towards the center of the valley.

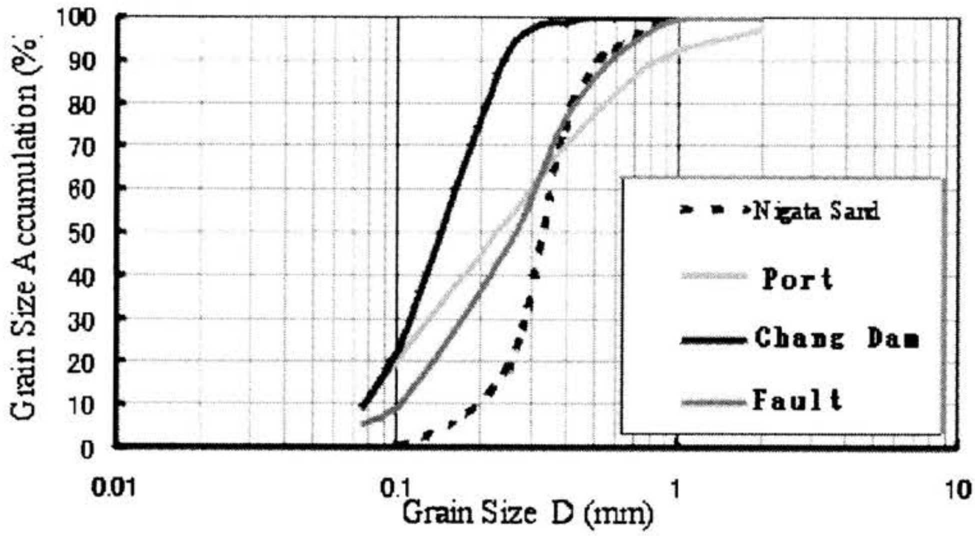


Figure 8.1. Grain size accumulation of the boiled-out sands

Cracks run along the longitudinal axis of the valley. The crack on the south embankment was mistakenly interpreted as the fault break. The crack is due to the lateral spreading of the ground (Photo 8.14(b)).

Figure 8.1 shows the grain size accumulation curve of the boiled-out sands at Kandla port, Chang dam and Chobari with the sand from Niigata City. The samples mostly consisted of liquefiable fine sands with mean grain sizes of 0.15 ~ 0.30mm, respectively.

8.6 Elevated Water Tank

Many of the systems have elevated concrete storage tanks that are on the order of 30m high (Photo 8.15). Most of the water tanks, which are elevated, did not suffer any substantial damage although severe damage could be observed at nearby buildings and structures. The water tank at Chobari village was toppled (Photo 8.16). The water tower was fallen in the direction of S30E. The location is 23° 31' 22"N;70° 20' 64"E. The water tank in Bachau town also survived the earthquake. The water tank in Anjar was an RC structure with four piers and built in 1955 with a capacity of 20000 gallons. It seems that there is more 250 water tanks in the region. However, 5 elevated tanks failed in the Malya-Morbi region south of the Gulf of Kutch. All the tanks are designed in the same state office. However, it is unclear why the failures in the Malya-Morbi area would have occurred and this deserves further investigation.

8.7 Conclusion

The authors presented an overview of the investigation by the reconnaissance team on the 2001 West India earthquake covered various aspects of the earthquake. Specifically, damage to infra-structures, geotechnical structures and lifelines have been described in this chapter. The outcomes and conclusions may be briefly summarized as follows:

- Widespread liquefaction was observed in the Rann of Kutch, the Little Rann of Kutch as well as the coastal areas of the Gulf in the vicinity of Ghandidham, Kandla, and between Malya and Samakhiali. Liquefaction was wide-spread particularly along the seashore, riverbeds, ponds and marshland and salt playas. The liquefaction has

Photo 8.15. Non-damaged typical elevated water tank in Bachau

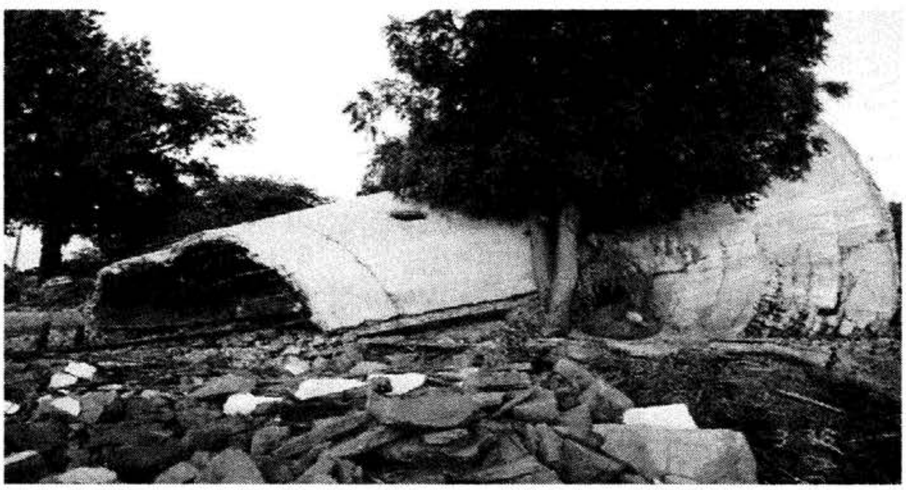


Photo 8.16. Collapsed water tank in Chobari village

manifested along long fissures and at many places it is of vent type. However, the structural damage due to liquefaction was quite limited in-spite of the huge scale of liquefaction.

- Most of the dams are earthen dams except a few, which is stone masonry, built. The dams are built for irrigation purposes. The dam failures were associated with the liquefaction of sub-soil along the old river course.
- Most of roadways had to be re-surfaced due to extensional and bulging type cracking. Furthermore, the settlement of embankments of bridges caused differential settlement and slows down of the traffic.
- Railway bridges were almost non-damaged. The only reported damage occurred at Bridge No.48 between Kukma and Bhuj and it was restored on 3rd Feb., 2001.
- Most of the minor/major roadway and highway bridges in Kutch region were damaged. Parapets of the minor and major bridges were totally or partially toppled or displaced in the entire region affected by the earthquake.

- The structural damage to Kandla, Navlakhi Ports was minor. No crane is toppled at the Kandla port. The Port Building on the piles near the main gate tilted with an inclination of 1-2 degree. Berths No.1 to 5 at Kandla Port have developed some structural damage. Berths No.6 to 9 are functional. The strong shaking damaged many piles supporting the docks of berths No.1 to No.5. The piles were cracked by the bending, and some concrete pieces were chipped from the pile tops.
- The 370MW lignite (coal) burning plants located in Panandhro about 180km northwest of the epicenter and they experienced only minor cracking while there was no damage to a coal-burning plant in Ahmedabad, 211km east of the epicenter. The Kakrapar nuclear power plants Unit No.1 (220MW) and No.2 in Gujarat State were in operation at the time of the earthquake, which was located about 400km southeast of the epicenters. The Kakrapar nuclear power plant suffered no damaged, and it did not stop supplying power just after earthquake.
- In the Anjar 220kV substation, the communications system and power protection system had failed when the battery rack collapsed. In the yard, all transformers derailed, some bushings were broken.
- Oil and chemical tanks were almost non-damaged. Damage to tanks mostly resulted from the settlement of foundation ground due to liquefaction.
- The stoppers or racks of the pipelines were either broken or buckled in the port area.