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V. S. Brahmabhatt
Narmada, Water Resources, Water Supply & Kalpsar Department, Government of Gujarat, Gandhinagar, Gujarat, India

V. M. Yagnik
Narmada, Water Resources, Water Supply & Kalpsar Department, Government of Gujarat, Gandhinagar, Gujarat, India

M. N. Dave
Narmada, Water Resources, Water Supply & Kalpsar Department, Government of Gujarat, Gandhinagar, Gujarat, India

P. A. Santwaani
Narmada, Water Resources, Water Supply & Kalpsar Department, Government of Gujarat, Gandhinagar, Gujarat, India

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CASE HISTORIES OF SOIL BEHAVIOUR AND INVESTIGATIONS FOR SEISMICALLY DISTRESSED EARTHEN DAMS OF KACHCHH REGION IN GUJARAT, INDIA

Brahmabhatt V. S. **Yagnik V. M.** **Dave M. N.** **Santwaani P. A.**
Narmada, Water Resources, Water Supply & Kalpsar Department, Government of Gujarat,
Gandhinagar, Gujarat (India)

ABSTRACT

In the morning of January 26, 2001, a devastating earthquake of magnitude M_W 7.7 rocked the Gujarat State of India. The disastrous earthquake claimed thousands of human lives besides widespread destruction of the properties including damages to water resources projects of Kachchh region. This worst ever natural calamity of recent time posed challenging and daunting task of restoration and reconstruction works. A committee of experts was constituted by Government of Gujarat with a view to assess the damages occurred to the dams & other appurtenant structures and to recommend restoration and reconstruction works. Consequent to the event, dams of Kachchh region situated within radius of 200 km from the epicenter were inspected as per the guidelines of International Commission On Large Dams (ICOLD). Integrated geotechnical investigation program comprising soil exploration and laboratory testing was chalked out to determine the properties of foundation & embankment soils. The paper describes the seismic data on Bhuj Earthquake, geology of Kachchh region, geotechnical investigation including assessment of liquefaction potential and their considerations in the restoration measures of two earth dams.

INTRODUCTION

A disastrous earthquake of magnitude M_W 7.7 struck Bhuj and adjoining areas of Kachchh region of Gujarat in India at 8:46:42.9 Hrs (IST) on January 26, 2001. The epicenter was located near Bhachau town about 65 km east of Bhuj in Kachchh region. The seismic activity was so intense that the shocks were experienced even in Delhi, Srinagar, Mumbai & Kolkata extending to the neighboring countries like Nepal & Pakistan. The main shock had a focal depth of 25km and was the largest seismic event of last 50 years, causing widespread damages to the structures. This seismic activity had caused profuse liquefaction covering an extensive area of 50,000 km^2 Large number of water resources projects located in Kachchh region were also damaged. The earthquake induced extensive liquefaction was observed in Holocene deposits. i.e. in alluvium, residual deposits and Rann sediments. Liquefaction features such as sand blows and lateral spreads were observed in some areas. Some fluctuations in the ground water table and ground water quality were also reported by the initial monitoring during the post earthquake period. There are 20 medium and 165 minor dams in Kachchh. Consequent to the earthquake, all dams of Kachchh region situated within radius of 200 km from the epicenter were inspected as per guidelines of International Commission On Large Dams (ICOLD). In many cases, longitudinal cracks of 3 to 5m depth and up to 25cm width, sliding of upstream slopes with settlement and buldging, settlement of pitching on slopes, transverse cracks and sloughing of upstream slope at river channel portion were noticed. The soil of Kachchh region is mostly sandy and silty. These soils, being mainly derived from sandstones, contain negligible cohesion and is of uniformly graded nature. Such soil in its full saturation condition is considered as potentially liquefiable soil. Adequate data of foundation & embankment soil properties and other parameters were not available for many of these dams. In order to facilitate design of embankment dams and provide remedial measures to counter probable liquefaction induced failure, it was necessary to generate sufficient soil data for foundation as well as embankment of each of the damaged dams.

BHUJ EARTHQUAKE

The epicentral parameters as determined by India Meteorological Department are given below:

Date	January 26, 2001
Origin time	08:46:42.9 (IST)
Epicenter	23.40^0 N, 70.28^0 E
Focal Depth	25 km (using depth phase)
Magnitude	M_L 6.9 (on Richter Scale)
	Mb = 7.0, Ms=7.6, Mw=7.7

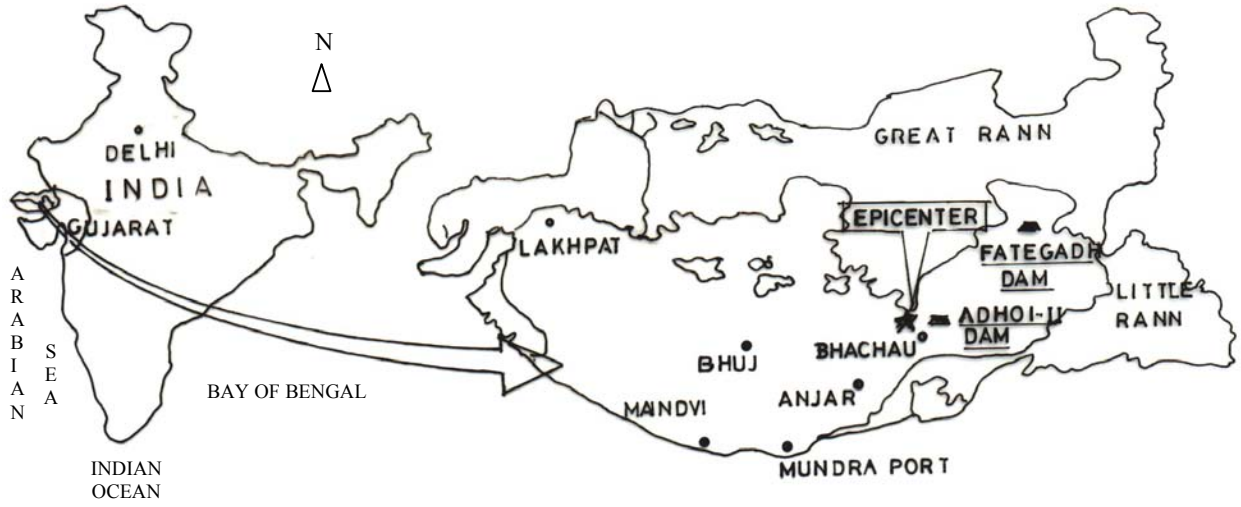


Fig. 1 Location of epicenter of Bhuj earthquake - Kachchh

The significant feature of this earthquake was that there were no foreshocks prior to main shock. However, there has been intensive aftershocks activity of moderate to slight magnitude following the main shock. The aftershocks are still felt even after period of over two and half years. Recently on October 11, 2003 aftershock of 4.1 magnitude on Richter Scale was recorded.

GEOLOGY OF KACHCHH

Kachchh region forms an important site for the Mesozoic (200 m. y.) and Cenozoic rocks (60 m. y. to 0.5 m. y.) The rock types are mainly sandstones, shales and limestones. The Mesozoic rocks ranging in age from Middle Jurassic to Lower Cretaceous occur conspicuously in the various major uplifts, and are exposed extensively in the Kachchh. The Deccan trap (60 m. y.) is restricted only to the Kachchh Mainland bordering Mesozoic highlands extending from Lakhpat in the west to Anjar in the east. Lava flows overlie the Jurassic sandstone, occupying the southern and south-western slopes of the central highland. The rocks form more or less linear outcrop with a maximum width of about 10 km. In the east near Anjar and gradually tapering west-ward. The Tertiary rocks (20 to 30 m. y.) are exposed along the coastal belt of southern and western Kachchh bordering the Mesozoic rocks.

These occur in the northern islands. The Quaternary (0.5 m. y.) deposition in Kachchh is rather poor and fragmentary. The related marine sediments are represented by aeolian accumulation of miliolites far inland from the coastline.

GEOTECHNICAL INVESTIGATION

Strategic soil investigation program was framed for the damaged dams. The soil investigations comprising soil exploration field work followed by laboratory testing was undertaken.

Soil samples were collected from bore holes drilled near the toe and heel (in gorge portion as well as on left and right of gorge portions) of each dam. Undisturbed samples were collected by Shelby tubes. SPT for determining 'N' values were carried out at an interval of 1.5m depth in each bore hole. More than 10,000 soil samples comprise undisturbed samples (Shelby), disturbed samples and core cutter samples were collected from dam foundation, body of dam and borrow area as per the design requirements. Borrow area samples were visually identified and tested to suit different zones of embankment dams. After in-house visual soil classification, the laboratory tests were performed which included Mechanical analysis, Atterberg Limits, Specific Gravity, Density, Shear tests (Box shear/Triaxial), Consolidation, Permeability & Cyclic triaxial. Where non-cohesive sandy / silty soil occurred, normal box shear test and box shear CD tests were performed and where cohesive soil was encountered, UU Triaxial and CU triaxial tests were performed. Moreover, in case of non-cohesive soils, the physical properties of samples were compared with three different standard liquefaction criteria advocated by Tsuchida (1970), N. V. Nayak (1979) and Jennings (1980) to judge their comparative liquefiability. Potentially liquefiable soil samples were then tested on cyclic triaxial apparatus machine to determine their cyclic shear strength to assess the resistance of foundation soil against seismically induced liquefaction.

SEISMICALLY INDUCED LIQUEFACTION

The soil investigation revealed that the foundation soil of majority of the earthen dams in Kachchh region is mostly sandy and silty having negligible cohesion and is of uniformly graded nature. In all the cases, upstream slopes are flatter than the downstream slopes and adverse seismic forces acted equally on both slopes in alternative half cycles. At the time of earthquake, the water levels in most of the reservoirs were well below the minimum drawdown level and there had been no rapid drawdowns in the recent past. Hence, it was felt that the foundation material which was fully saturated in the gorge portion on upstream of cut off trench developed high pore pressures during the earthquake resulting in loss of shear strength or liquefaction to variable degrees, which subsequently resulted in long and wide moon shaped cracks and heavy subsidence in many cases. On the downstream of the cut off trench, the soils were not in saturated condition and hence liquefaction effect was not fully triggered in this portion. This is also confirmed by observing comparatively more damages on up stream side and that too in the gorge portion than that on the downstream side. Besides the liquefaction phenomenon, the acceleration and deceleration cycles generated by earthquake have also generated horizontal shear forces and they might have caused cracking even without a tendency for liquefaction. However a study of the pattern of damages leads to the inescapable conclusion that in several cases liquefaction also took place.

For assessing liquefaction potential of the foundation soil of different dams, Seed's simplified approach (1975) was employed. The cyclic shear strength in terms of cyclic stress ratio required for causing liquefaction was derived from laboratory experimental study. The induced cyclic shear forces are calculated for recent earthquake parameters. Factor of safety against seismically induced liquefaction is then calculated by comparing cyclic shear strength with induced cyclic shear forces.

The case histories of Fategadh medium irrigation scheme and Adhoi II minor irrigation scheme which represent the overall scenario of seismically distressed dams, their geotechnical investigation and restoration works are discussed in the following paragraphs.

CASE HISTORY NO.1:

FATEGADH MEDIUM IRRIGATION SCHEME

The salient features of the dam are as under:

Location		
1)	Latitude	23^0 41' 0" N
2)	Longitude	70^0 47' 20" E
3)	Epicenteral distance	74 km
4)	River	Malan
5)	Year of completion	1982
Hydrology		
1)	Catchment area	103.60 km^2
2)	Max. Design Flood	280.40 m^3/s
Reservoir		
1)	Gross Storage Capacity	7.45 Mm^3
2)	Full Reservoir Level	22.70 m
3)	High Flood Level	25.20 m
4)	Reservoir Level on 26/01/2001	19.10 m
Head Works - Dam		
1)	Type	Zoned earth dam
2)	Length	4130 m
3)	Top Width	6 m
4)	Maximum Height	17.13 m
5)	Upstream Slopes	2.5 : 1
	Downstream Slopes	2.5 : 1
Waste weir / Spillway		
1)	Type	Chute Spillway
2)	Length	35 m
3)	Crest Level	22.70 m
Irrigation		
1)	C. C. A.	919 ha

GEOLOGY

At the dam site, horizontally disposed sedimentary rock formations of Tertiary age is exposed. Predominantly clayey shale/clay with friable sandstone/sand rock is exposed below 0.60 to 3.60 m thick overburden soil. Both the rock types are weathered. The sandstone is friable and clayey shale is soft.

EARTHQUAKE INDUCED DAMAGES

After the event of earthquake, the dam was inspected by the Panel of Experts. The distressed features observed are shown in fig. 2 and described below:

- Prominent longitudinal cracks on the crest and upstream slope.
- Most prominent was the deep crack near the center of the crest extending about 10m in one stretch, between ch. 3550 m and ch. 3700m (deep river channel portion). This crack had been measured up to 1.4 m depth and about 40 cm wide at the crest.
- Noticeable longitudinal crack at the center of the crest at ch. 3700m, measuring up to 3m depth.
- Prominent and noticeable slips of the upstream edge of earth dam in the deep river portion, showing acute slump of the slope and scrap up to 5m depth. Sand blows in the down stream portion. These are clear indication of liquefaction.
- Few transverse cracks with differential settlements near the junction of spillway and earth dam.

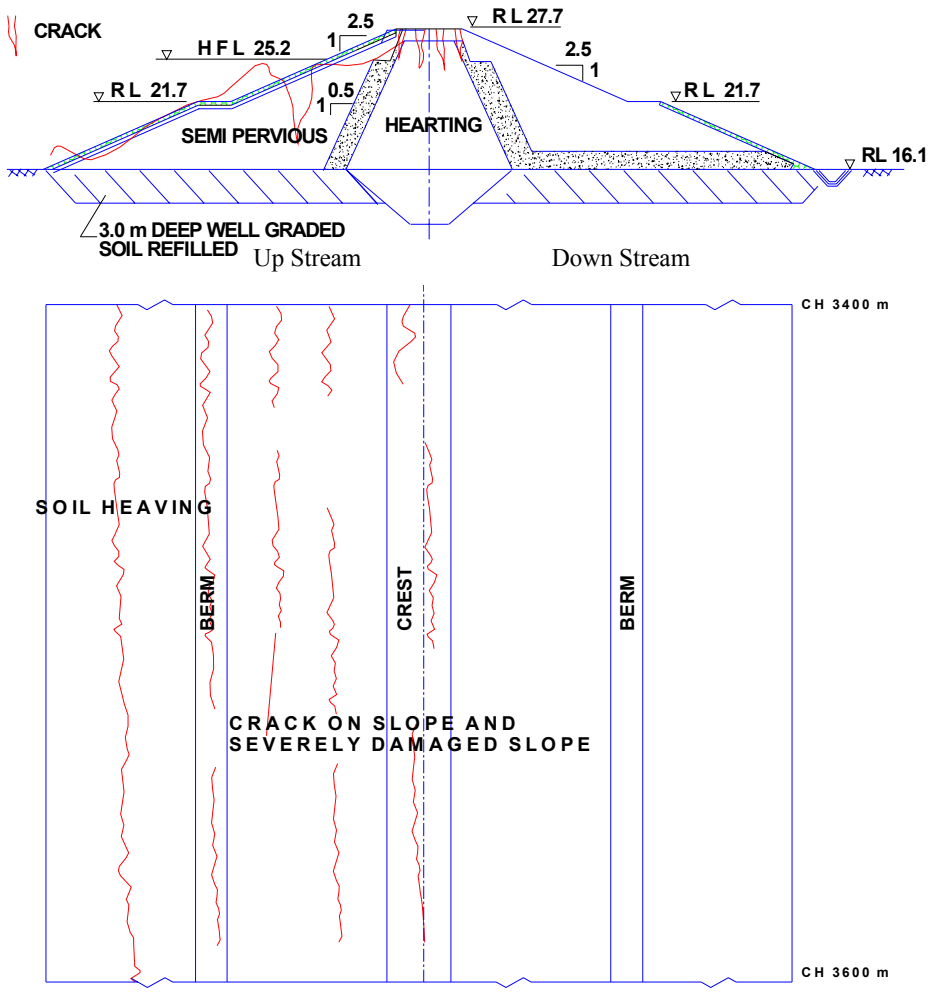


Fig. 2 Earthquake damages and restoration works of Fategadh dam.

SOIL INVESTIGATIONS

Detailed soil investigation of the existing dam, borrow area and foundation soil for restoration were carried out as discussed earlier. The design soil parameters used for the design analysis are given below in Table 1.

Table 1: Design soil parameters

Sr. No.	Zone	Density kg/m^3	Moisture %	C kg/m^2	∅ degree
1	IP	1640 (FDD)	2.0 (FMC)	5000	22
2	SP (Exist)	1670 (FDD)	3.10 (FMC)	0.0	30
3	Rock	1700 (MDD)	8.00 (OMC)	0.0	36
4	Foundation	1670 (FDD)	17.00 (FMC)	0.0	29
5	SP (New)	1990 (MDD)	9.2 (OMC)	0.0	30

Based on these test results the design parameters for different zones of the Earth Dam section and foundation soil were evaluated.

Seismic Design Parameters:

As per the provision in the national code (IS: 1893-1984), the following seismic design co-efficients were adopted in redesigning for strengthening the dam.

Seismic zone factor, Z	=0.4
Maximum Sa/g	=0.16
Importance factor I	=2.5
Seismic design co-efficient	=0.16 (with 1=2.5)

RESTORATION BASED ON STABILITY ANALYSIS

For carrying out stability analysis of earth dam section, the full reservoir level (FRL) and minimum water level (MWL) were considered as 22.70m and 25.15m respectively. The tail water level (TWL) and minimum drawdown level (MDDL) were considered as 20.30m and 20m respectively.

The stability analysis of existing earth dam revealed that upstream slope could be unsafe against earthquake loading. Therefore, additional rock zone was provided and the values of final factor of safety worked out are given in Table 2.

Table 2: Factor of safety

Slopes	Condition	Factor of Safety			
		Arrived after Redesign		Allowable	
		With out considering E. Q.	Considering E. Q.	With out considering E. Q.	Considering E. Q.
Up-stream	Construction	1.429	-	1.00	-
	Operating	1.722	1.002	1.50	1.00
	Sudden draw down	1.445	-	1.30	0
Down stream	Construction	1.34	-	1.00	-
	Steady seepage	1.593	1.028	1.50	1.00

RESTORATION CONSIDERING LIQUEFACTION

As described earlier, SPT were carried out in 6 different bore holes. Results of one typical bore hole drilled at ch. 3600m on upstream are given in Table 3.

Table 3 : SPT values in Bore hole

Sr. No.	Depth from G. L., m	'N' values
1	1.45	3
2	2.95	6
3	4.45	16
4	5.95	14
5	7.45	16
6	8.95	20
7	10.45	24

One typical result of laboratory cyclic triaxial test carried out for the sample at Sr. No.7 are also given as under.

Epicentral distance	68.4 km	
Maximum horizontal ground surface acceleration	0.20g	Parameter considered
Cyclic Stress Ratio causing liquefaction $(CSR)_c$	0.1263	Experimentally determined
Induced Cyclic Shear Stress Ratio $(CSR)_i$	0.1884	Empirically determined
Factor of safety	0.6704	Derived

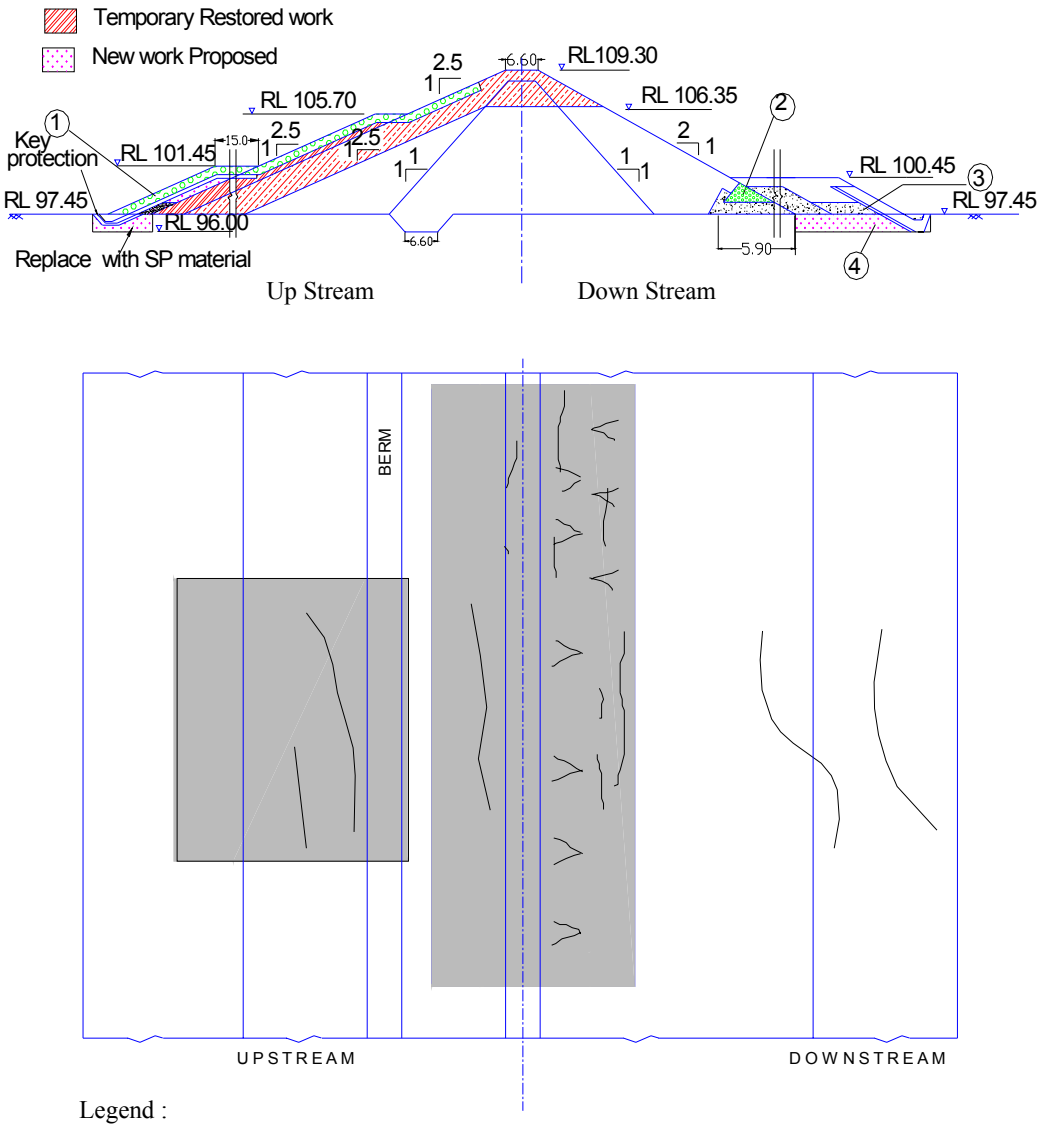
Values of SPT were taken into consideration while finalizing the section of the earth dam. In accordance with clause 3.3.3 of Indian Standard (IS) No. 1893-1984, for the depth up to which the SPT values did not meet the requirements of the code (10.45 m in this case), the existing soil was excavated and replaced by compacted soil to achieve the desired SPT values.
At Ch. 3600m, down to 5.95 m depth from ground level SPT values were ranging from 3 to 14. The loose layer of this zone was therefore compacted by driving timber piles in a area of radius of 10 m around the location of the specific bore hole.

CASE HISTORY NO. 2:

ADHOI-II MINOR IRRIGATION SCHEME

The salient features of the dam are as under

Location		
1)	Latitude	23^0 25' N
2)	Longitude	70^0 34' E
3)	Epicenteral distance	25 km
4)	River	Local
5)	Year of completion	1987
Hydrology		
1)	Catchment area	4.66 km^2
2)	Max. Design Flood	1.81 m^3/s
Reservoir		
1)	Gross Storage	0.59 Mm^3
2)	Full Reservoir Level	32.34 m
3)	High Flood Level	32.89 m
4)	Reservoir Level on 26/01/2001	24.3 m
Head Works - Dam		
1)	Type	Zoned earth dam
2)	Length	156 m
3)	Top Width	3.96 m
4)	Maximum Height	11.87 m
5)	Upstream Slope	2.5 : 1
	Downstream Slope	2 : 1
Waste Weir/Spillway		
1)	Type	Ground bar
2)	Length	45 m
3)	Crest Level	32.34 m
Irrigation - C. C. A.		161.94 ha



Legend :

① 0.45 m thick pitching is to be provided over 0.30 m thick graded filter
② Existing rock toe and filter
③ Toe protection as per IS 9429 – 1999
④ Sand filter

Fig. 3 Earthquake damages and restoration works of Adhoi - II dam.

GEOLOGY

In the vicinity of the dam site, sandstone and shale belonging to Tertiary age are exposed. The sedimentary beds are horizontal in disposition. Sandstone occurs as thick beddings whereas shale beds are thin. Sandstone is pebbly and ferruginous in nature and at the ground bar waste weir location Due to removal of coarse sand grains and pebbles, the sandstone is imparted pitted appearance on the exposed surface. The rock formation is weathered at the surface.

EARTHQUAKE INDUCED DAMAGES

After the event of earthquake, the dam was inspected by the Panel of Experts. The distressed features observed are shown in fig 3 and described as follows.

- Series of cracks on top of the dam as well as on upstream and downstream slopes in the gorge portion. The cracks were about 30 to 40 m long, 15 cm wide and over 1 m deep.
- The pitching was heavily disturbed.
- Top of the dam settled by 1 to 1.5m in about 65m length in gorge portion. Slopes were sloughed.
- Peripheral crack was seen along upstream of the dam and all along low level reservoir boundary where slips occurred. Sand blows were noticed in the basin area. These were clear indications of liquefaction phenomenon.

SOIL INVESTIGATIONS

Detailed soil investigations of the existing dam section, borrow area and foundation soils for restoration were carried out as discussed earlier. The design soil parameters used for the design analysis are given in Table 4.

Table 4: Design soil parameters

Sr. No.	Zone	Density kg/m^3	Moisture %	C kg/m^2	∅ degree
1	IP	1570 (FDD)	3.00 (FMC)	4000	28
2	SP (Exist)	1770 (FDD)	6.00 (FMC)	0	29
3	SP (New)	1615 (MDD)	10.00 (OMC)	0	34

Based on these test results the design parameters for different zones of the Earth Dam section and foundation soil were evaluated

Seismic design parameters considered in this case are same as discussed in Case study-1 earlier.

RESTORATION BASED ON STABILITY ANALYSIS

For carrying out stability analysis of earth dam section, the full reservoir level (FRL) and minimum water level (MWL) were considered as 105.75 m and 107.55 m respectively. The tail water level (TWL) and minimum drawdown level (MDDL) were considered as 97.45 m and 100.50 m respectively.

Stability analysis of existing earth dam revealed that upstream slope could be unsafe against earthquake loadings. Therefore, additional earth work was provided on existing upstream and downstream slopes. With additional earthwork, the values of final factor of safety were calculated as given in Table 5.

Table 5: Factory of safety of earth dam

Slopes	Condition	Factor of Safety			
		Arrived after Redesign		Allowable	
		With out considering E. Q.	Considering E. Q.	With out considering E. Q.	Considering E. Q.
Up-stream	Construction	1.851	1.003	1.500	1.000
	Sudden draw down	1.151	-	1.300	-
Down stream	Steady seepage	1.506	1.045	1.500	1.000

RESTORATION CONSIDERING LIQUEFACTION

As discussed earlier, standard penetration tests (SPT) were carried out in 6 different bore hole. Results of one such bore hole drilled at 12m upstream of ch.190 m are given below in table 6.

Table 6: SPT values in bore hole

Sr. No.	Depth from G. L., m	'N' value
1	1.45	13
2	2.95	19
3	4.45	19
4	5.95	18
5	7.45	25
6	8.95	28
7	10.45	33

The parameters considered from the results of laboratory cyclic triaxial test carried out for the sample at Sr. No.7 are given below.

Epicentral distance	68.4 km	Parameter considered
Maximum horizontal ground surface acceleration	0.20g	
Cyclic Stress Ratio causing liquefaction $(CSR)_c$	0.1763	Experimentally determined
Induced Cyclic Shear Stress Ratio $(CSR)_i$	0.1966	Empirically determined
Factor of safety	0.8970	Derived

Values of SPT were taken into consideration for finalsing the dam section. The minimum 'N' value is 13 at 1.5 m below ground level otherwise the 'N' values below G. L. are high. For stability of earth dam 8 m and 6m wide loading berms at R. L. 101.45 m and 100.45 m on up stream and down stream respectively were provided, at some locations they were extended up to 10 m and 15 m width on up stream and down stream respectively at above levels considering the

liquefaction aspects. It was also decided to remove the soil down to 1.5 m depth from the ground level in the new earthwork and same to be filled up with semi-previous material in upstream side and with sand in downstream side.

CONCLUSIONS

- Detail soil investigations and parameters derived reveled that existing slopes of distressed earth dams in Kachchh region were not safe from the seismic design consideration. Seismic design parameters are now considered for slope stability analysis.
- As per Seismic Zoning Map of India (IS: 1893-1984), Kachchh falls in seismically active zone V. Majority soils of this region are more or less uniformly graded non-cohesive soil (sandy & silty) which is vulnerable to liquefaction. 'N' Values determined from SPT and cyclic triaxial on this soil samples also confirm that soil is potentially liquefiable. The results have helped in redesigning for the rehabilitation of the damaged dams considering this factor.
- Embankments suffer damage or failure may occur due to existence of potentially liquefiable soil strata below the seat of dam. When potentially liquefiable soil found in the foundation / dam seat portion, proper analysis / testing need to be conducted to ascertain the requisite factor of safety against liquefaction. Accordingly, necessary remedial measures should be adopted.
- Due consideration to the foundation strata is given in gorge portion / river channel portion, as more damage was observed in that portion during the recent earthquake.
- Where embankment was poorly compacted, remarkably a few slides were observed on upstream slopes.
- Earth dams with central masonry/concrete core walls were badly cracked by earthquakes due to phase vibrations of masonry/concrete wall and adjoining earth works.
- The amplitude and the acceleration of the horizontal component of the movement of the crest is much larger than the movement of the foundation. This results in a "whipping' or ' Ridge amplification" action of the thinner top of the dam and causes longitudinal cracks.

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