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ASSESSMENT OF DAMAGE AND REHABILITATION OF SMALL AND MEDIUM EARTH DAMS

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SUMMARY

The devastating earthquake of January 26, 2001 of magnitude Mm=7.7 occurred at a focal depth of 25 km near Bhuj where large number of earth dams and appurtenant works in Kachchh and Saurashtra districts were damaged which are meant for irrigation and water supply. The causes of damage, restoration and strengthening of large number of damaged dams are discussed. Based on the soil tests and the pattern of damages lead to the firm conclusion, that in several cases, damage to dams was mostly attributed to severe vibration and liquefaction of the sub-soil. The rehabilitation of these dams was taken up in two stages. In Stage I, temporary restoration was carried out to bring the 'repairable' dams back to safety without much change in earth dam section to enable them to store water in monsoon. In Stage II long-term restoration of scheme was carried out with earthquake resistant design, restoration and upgrading all the components of the projects. The paper also presents detail of restoration and rehabilitation procedures adopted.

INTRODUCTION

The devastating earthquake of January 26, 2001 of magnitude Mm=7.7 occurred at a focal depth of 25 km near Chaubari 30 km from Bhachau. It caused widespread devastation in terms of lives lost (13811) and property damage. Mostly the masonry buildings were damaged or collapsed as a result, of which the human as well as cattle lives were lost. The damage was very severe in the district of Kachchh. Large tracts of region in the Rann of Kachchh had experienced liquefaction, sand boils and extensive ground cracking. Large number of earth dams and appurtenant works in Kachchh and Saurashtra districts were also damaged which are meant for irrigation and water supply. This earthquake has thus provided an opportunity for a systematic study of the damage of all these dams in Kachchh and Saurashtra regions. Immediately after the earthquake, Government of Gujarat constituted a Committee of Experts to inspect and assess the earthquake damage to the dams and the appurtenant works and to recommend initially temporary restoration works before the monsoon and then recommend for the complete rehabilitation and upgradation of dams in accordance with latest concepts and methodology. In the mean time, the World Bank, in April 2001, offered to fund the Dam Rehabilitation and Upgradation Project especially to the dams located in Kachchh and Saurashtra regions of Gujarat, which were badly affected by the earthquake. Two separate Dam Safety Review Panels i.e. one for Kachchh region and another for Saurashtra region were constituted by the Government of Gujarat. All the 20 medium dams damaged in Kachchh region and

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all the 37 old dams damaged in Saurashtra region by earthquake were visited by the Dam Safety Review Panels.

In recent times, large numbers of earthen embankments were damaged during the Bihar-Nepal earthquake of August 21, 1988 and Bhuj earthquake of January 26, 2001 of magnitude Mm=7.7. The Bhuj earthquake has revealed that recent dam constructed with modern techniques has behaved much better than the old dams. Though the new dams constructed with modern techniques perform well during earthquakes, there is large number of inventory of unsafe old earthen dams, which need to be seismically upgraded. This paper describes the common damages to earthen dam, their causes of failure and suggests suitable seismic techniques for retrofitting the old earthen dams.

SEISMICITY OF KACHCHH AND SAURASHTRA

The Kachchh main land is highly seismic and lies in seismic Zone V according to IS: 1893: 2002. The main structural features responsible for the present architecture of Kachchh are a group of E-W trending faults viz. (i) the Allah bund fault, (ii) the island belt fault, (iii) the Kachchh mainland fault, and Katrol-Bhuj Fault. Kachchh has long history of major earthquakes. The Saurashtra region of Gujarat forms an independent seismotectonic and geological domain in Gujarat and very much distinct from Kachchh main land. It is bounded by geotectonic faults on the North by the East-West trending North Kathiwar fault; on the West and South by coastal faults and on the East by West Coast Fault. Except for the northern coastal parts adjoining the Gulf of Kachchh, which is in seismic Zone IV, the rest of Saurashtra is in Zone III. Saurashtra plateau has experienced earthquakes of magnitude greater than 5.

Iso-seismals drawn by GSI for Kachchh earthquake of Jan. 26, 2001 show that most part of the Kachchh was subjected to MSK intensity IX and most part of Saurashtra was subjected to MSK intensity VII. The Structural Response Recorders (SRR) installed in 1980’s by Department of Earthquake Engineering, University of Roorkee covering the presently affected areas gave very valuable instrumental data about the intensity of shaking in terms of Peak Ground Acceleration (PGA) at various locations. The maximum peak ground acceleration at the epicentre is estimated about 0.65g that corresponds to very severe intensity of shaking. The earth dams near the epicentral region were therefore subjected to very high intensity of shaking.

DAMAGE TO EARTH DAMS

Cases of earthquake damage in earth dams are numerous. Some of the important dams, which have failed during earthquake, are Sheffield dam (height 9m) and Hebegen dam (height 26m). An earthen dam in Chile which withstood the earthquake with low reservoir level in 1965, failed in 1971 in equally strong earthquake when the reservoir level was high. Middlebrooks [1] has tabulated about 200 earth dams which have failed or whose performance has been unsatisfactory. Less than 20 dams were built after 1925. The most common causes of failures were either overtopping or piping. Both of these causes are of minor concern in dam design now. However, not much has been understood of the effect of earthquake on earth dam and hence no rational design criterion has been used in the dams constructed upto 1950 or so.

Failure of San Fernando dams, USA

San Fernando earthquake of February 9th, 1971 caused major slope slides in the two dams (i.e. San Fernando and Chabot dams). The Lower San Fernando dam 42.7m high at its maximum section, had water level about 11m below its crest at the time of the earthquake. The slide movements resulting from the earthquake shaking involved both the upstream slope and the upper part of the downstream slope, leaving only about 1.5m of freeboard. The upper part of the remaining embankment contained several large longitudinal cracks and the upstream face of the slide scarp was almost vertical. Construction of this dam was started in 1912 and it was raised to about 25.5m in height in three years, by hydraulic-fill methods. During the following year an additional 4.5m of ground-up shale was added by the same procedure and in the period from 1916 to 1930 rolled-earth fill was added to raise the height to 42.7m. Thereafter, in 1940, a rolled-earth berm was added on the lower part of the downstream slope.

The downstream slide in the upper San Fernando dam (24m) was somewhat less serious. The downstream movement led to some cracking of the embankment opening up of joints in the outlet conduit through the embankment and formation of a sinkhole along the line of the conduit due erosion through these joints. Though the crest moved downstream about 1.5m and settled about 0.9m there was no breach resulting in loss of water from the reservoir.

Failure due to landslide around reservoir rim

As long as the landslides actuated by earthquakes are small around the reservoir rim, they are not much of problem. Large slide in the impounded reservoir may lead to serious problems. Although not due to an earthquake, a large-scale landslide occurred at Vajont Dam in Italy on October 9, 1963, shortly after water storage began. A volume of 250 million cubic meters slid and the overflowing reservoir water struck the town of Longarone, killing 2, 125 persons. Similar, accident occurred in Alaknanda valley in India in 1978.

Damage to embankment during Bihar-Nepal earthquake

The 180.5 km long Kamla Balan embankment located on river Kamla is 6m high and 6m wide at the top having 1:2 slope on the river side and 1:3 slope on the country side with brick pitching on both sides was constructed a year before the earthquake of 1988 struck. The earthquake caused longitudinal cracks on the top of the embankment at several locations totaling nearly 7.5 km. At several locations the top and side slope subsided by 1.25 to 2.5m thereby causing great threat to overtopping of floodwater. The pitching at several places also bulged out. Liquefaction was also observed at several locations [Thakkar *et al.* [2].

The Bhutani Balan embankment is having 1:2 slope on river side with brick pitching over 15 cm filter material and 1:3 slope on country side without pitching. Longitudinal cracks of 7.5 to 15 cm wide developed at the top of embankment. Out of the total length of 50 km of embankment, nearly 26 km has been badly affected. Liquefaction seems to have occurred on both sides of the embankment. Apart from these other embankments (Bagmati, Kothauri, Gupta-Lakhmina and Koshi embankments) also showed longitudinal cracks at the top.

Damage to earth dams during Bhuj earthquake

The damage to earth dams was observed to depend upon the intensity of shaking (distance from epicenter), geological and geotechnical conditions at the site (foundation and overburden conditions); and design and construction; physical properties of the materials of the dam body and the foundation. Most of the Kachchh region was subjected to MSK intensity ranging VII to X and most part of Saurashtra was subjected to MSK intensity ranging V to VIII.

There are 185 irrigation schemes (20 medium and 165 minor) in the Kachchh district, which sustained damage in varying severity ranging from very serious to moderate. Out of these, 4 were critically damaged, 41 heavily damaged and 140 moderately damaged. The earthquake affected another 60 dams out of 140 dams in Saurashtra region. It was pointed out that out of 60 dams in Saurashtra region, 23 dams were of recent construction whereas the remaining 37 dams were old dams. Figure 1 shows the locations of the dams Paul *et al.*[3].

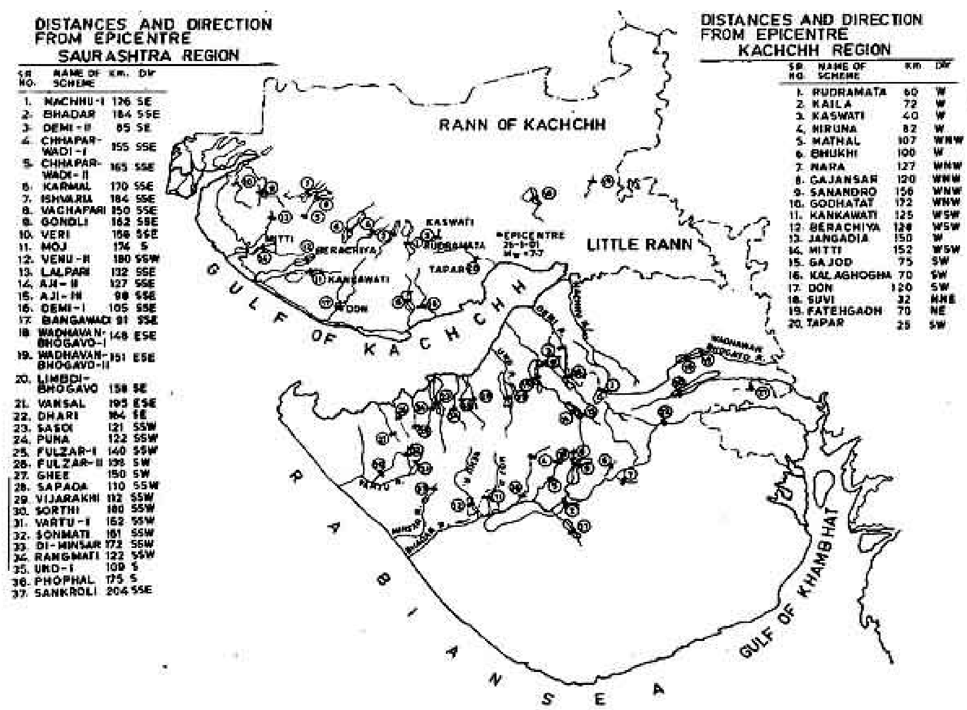

Fig. 1 Map of Kachchh and Saurashtra regions with dam locations

The dams less than 15m with chute spillways or ground bar waste weir are classified as minor dam. The heights of most of these medium and minor dams are less than 30.0m and generally constructed by the local community, which were not completely engineered. Figure 1 shows the location of dams in Kachchh and Saurashtra regions. Rudramata, Kawasaki, Fatehgarh, Suvi, Tappar, Chang, Don and Shivlakha dams were severely damaged. The pattern of the damages was found to be more or less similar as described below:

1. Settlement of the top crest of dams resulting in reduced free board making it susceptible to overtopping during high floods.
2. The u/s pitching on slopes has depressed in a sink like formation at several places. It bulged and slid in some of the dams resulting in depressions and deposition, which were badly damaged in the gorge portion. Figure 2 shows deep crack of a typical dam slope. The u/s slopes damaged much more than d/s slopes.
3. Slippage of the u/s slope as observed in many dams. In some cases leakage is also observed. Longitudinal cracks were also observed on the u/s slopes in the casing zone (Fig.2(a)). Sometimes there were series of parallel longitudinal cracks on the slopes. Most of the earth dams were badly
4. damaged in the gorge portion in the form of longitudinal and transverse cracks, displacement and settlement. These cracks do not show a settlement and look like tension cracks and not incipient slips.
5. The longitudinal crack at the dam crest, which was very deep in regions of high intensity of ground shaking (Figure 2(c)).
6. The transverse cracks in some of the dams are more serious as they may result in leakage and failure (Figure 2(b)).
7. Sink like depressions were also caused by ground shaking due to earthquake or due to seepage channels inside the earth mass.

8. Earth dams having rubble masonry core wall have shown extensive damage. Although, the rubble masonry core wall could not be seen, it would be reasonable to assume that it may have cracked due to out of phase vibrations of masonry core wall and the earthwork.
9. Extensive damage to dam section in the gorge portion also occurred due to loss of strength in foundation soil due development of excess pore water pressure leading to liquefaction in many cases.
10. The damage to parapet walls, spillway structure, abutment training walls, intake head regulator and approach bridges were common.

Fig.2 (a) Wide craks on the slope (b) Transverse cracks on the the dam crest, (c) Longitidinal cracks on the dam crest

CAUSES OF EARTH DAM DAMAGE/ FAILURE

Earthquakes are usually the most severe test to earthen dams. The performance of embankment dams subjected to earthquakes depends upon site characteristics and foundation conditions; geometry and materials of the fill; internal and external water pressures; and characteristics of the input earthquake motions, including their duration and their frequency and amplitudes. Mainly these factors determine the performance of the dam. Sherard [4] and Seed [5] list some of the possible ways in which an earth dam might be damaged or failed during an earthquake.

The damage to earth dams in Bhuj earthquake was in accordance with the intensity of shaking. Dams near to epicentral tract were damaged more severely. Being close to the epicenter, the damage to earth dams in Kachchh district is generally severe, while slight to moderate damage to earth dams was observed in Saurashtra. A few earth dams were completely damaged and many were severely damaged during the earthquake. The earth fill dams specially with masonry core have shown more earthquake damage than clay core dams. Comparatively more damage was observed on u/s slopes than that on the d/s slope.

The dams with natural time period of vibration close to the predominant frequency of the ground motion are likely to undergo severe damage. The natural period of vibration of dams of height ranging from 10 to 30m above toe level will be around 0.3 to 0.75 sec (assuming the average value of modulus of rigidity of 1500 t/m^2 for the dam material). The earthquake waves carrying the damaging energy are also maximum around the same range of periods and therefore earthen dams of this size are expected to undergo severe damage as has been observed. The common damages to the earthen dams include longitudinal and transverse cracks, settlement, and disturbance of the pitching due to intense shaking and liquefaction.

The development of high pore pressures in the foundation, reducing the shear resistance may have also caused damage. Eruption of sand-water fountains and boiling in the reservoir area was observed during the earthquake. The SPT values determined at dam foundation exhibit N values more than 10 in most cases but at few locations N was found to be less. Hence, the local occurrence of liquefaction of foundation soil was one of the causes of damage seen in Rudramata, Kasvati and Tappar dams in Kachchh. Prasad *et al.*[6]also carried out field investigations on Ratiya and Chang dams using Swedish Penetration Test and concluded that damage to these dams were mostly due to poor sub-soil. Failure of sub-soil resulted in embankment failure.

SEISMIC SAFETY STUDY

Safety evaluation of dams based on deterministic-statistical method applied to known causative faults provides an appropriate level of conservatism and is generally adopted. The seismic safety of dam is evaluated for following two earthquake environments, 13th ICOLD [7].

i) The dam is designed for Design Basis Earthquake (DBE) ground motion, which is defined as the intensity of ground shaking that has a significant probability of occurring in a period of about 100 to 200 years (the expected life of dam). For this earthquake loading there should be no significant damage. Some yield and permanent distortions may occur without impairing the strength of the dam.

ii) The dam should be checked for the Maximum Credible Earthquake (MCE) and ensure that it may not lead to catastrophic failure; however, it may undergo limited damage. Some damage to its appurtenant structures not critical to the stability of the dam may be expected.

Sherard [4] outlined the procedure for embankment dam design against the earthquakes so that the excessive deformation does not take place (slumping, settlement, cracking of the embankment, slope failures). Seed [5] developed analysis procedure for loose or medium dense saturated sand. Failure due to excessive settlement and movement of dam are possible modes of failure during earthquake. This type of failure can be expected when the dam rests on weak foundation and therefore a more conservative approach is used in such situations. Earthquake may result in formation of cracks in the dam leading to leakage. This may be due to differential settlement, movement of faults or severe shaking. For seismically safe design, the dam has to be protected against the excessive settlement, cracks and liquefaction.

SEISMIC EVALUATION

Proper inspection of any evidence of displacement, bulging, depressions or undue settlement, tilting, slope instability, cracks, seepage, leakage, erosion and improper functioning of drains and relief wells is required. Any of these conditions, if corrective measures are not taken, can ultimately lead to failure of the dam. Surface cracks near the embankment or embankment abutment contacts can be an indication of settlement of the embankment, and if severe enough, a path for leakage can develop along the contacts. Therefore, these crack locations must be thoroughly examined. Following procedure should be adopted for restoration works of earthen dams.

In seismic evaluation of a dam, it has to be ensured that sufficient defensive measures are incorporated by ensuring good quality control, adequate compaction of materials, foundation and abutment integrity, ample freeboard, provision of gentle u/s and d/s slope.

It is necessary to review the design of small dams in accordance with IS: 1983-2002 and undergoing site specific seismic studies for major dams so that the stability of dams can be checked. In most cases the seismic coefficient and importance factors adopted in the initial design may not be available.

In order to assess the earthquake safety as per the current Code of practice, stability analysis of the earth dams should be carried out considering the fresh test results on the insitu foundation, core and shell materials. The test results include field dry density, moisture contents; shear strength parameters i.e. cohesion c and angle of internal friction ϕ. Liquefaction potential tests on dam materials at some locations should also be carried out. These tests include determination of SPT values. Wherever necessary soil tests of the existing earth dam section and the newly identified borrow area soils to be used for rehabilitation of dam should be undertaken. The shear parameters should be used in the stability analysis based on these tests values.

The analysis of dam permits the detection of zones, which are vulnerable as regards to deformation and stability (Gazetas [8], Newmark [9]) On the basis of such a study, it is possible to provide for anti seismic measures in the design. One of the simplest measures is flattening the slopes in the upper portion of dam and additional earthwork both on u/s and d/s sides. Another most commonly used measure from stability consideration involves filling of well-compacted material on the slopes because these zones are very unfavourable from stability considerations. Very well compacted rock mass from hard rock material fulfills this task. At surface stresses are small and the compacted rock mass has large angle of internal friction. This property has significant importance.

REPAIR AND RESTORATION MEASURES

All the 20 medium dams in Kachchh and all the 37 old dams in Saurashtra affected by earthquake were restored and retrofitted (Paul *et al.* [10]) Following procedure have been adopted for repair and restoration of earthen dams (Arya and Paul [11])

1. All the bushes and other foliage on the dam slope and the channel sections are to be cleared.
2. An all weather jeep-able bitumen coated road with a 0.3m high kerb on the downstream edge of the dam be provided and maintained so as to reach the dam site during the floods particularly in case of emergency.
3. Rainwater be guided along the downstream kerb in a longitudinal drain and guided on downstream slope along proper-pitched drains to join the downstream toe drain.

4. The rock toe be restored and toe drain provided. Arrangement for seepage measurements be made in the toe drain.
5. The earth dam sections shall be checked to conform to the norms, specified in the BIS. The dam section shall also be checked so as to conform to the seismicity of the region as per IS: 1893-1984.
6. Additional free board is provided where required by constructing parapet wall along the upstream edge of the dam crest or increasing the height of the dam.
7. The cross-sections of earthen dam shall be taken at 100m intervals, on which the designed sections shall be superposed for making up and redressing the section to correct profile.

RETROFITTING MEASURES

The repair and retrofitting may not be adequate and many cases strengthening may be needed to bring the dam to desired seismic strength. To enhance the stability at some locations, berms beyond the present rock toe on the downstream and a toe drain may be provided in the existing section. The other measures include increasing the width of dam crest, placing additional shell material on the d/s slope at a flatter slope of 3:1 with berms along with a horizontal sand filter under the new shell material and a toe drain at the new toe position. The guidelines for rehabilitating the dam are given as follows (Reports of DSRP, GOG[12,13,14]; Paul [10])

Treatment of cracks

Wherever some sort of cracking or separation is visible, though in the form of hair cracks, those cracks should be investigated in detail and appropriate remedial works be carried out. To investigate a crack, it is suggested to excavate a trench or trial pit, 3m deep exposing top of impervious core, the trench to be further dug for 0.5m depths in impervious core. Fill the trench made in impervious core with water and allow water to seep through. Observe the u/s toe; u/s wing wall and d/s toe at end of junction for signs of wetness or oozing of water. If at all any sign of wetness or oozing is found then the u/s slope surface from toe towards top of dam and upto u/s face of key is trenched upto 3m depth adjacent to abutment wall. The side slope of trench on earthwork side is kept as 0.5:1 and bottom width be kept as 1.0m. The trench is back filled with mixture of impervious soil and 2% to 3% of low-grade bentonite to be laid and compacted with hand held pneumatic tempers at 2% of optimum moisture content and upto a depth of 1.5m. The upper 1.5m layer over core material is backfilled with semi-pervious type of soil with compaction by pneumatic temper. The riprap is then re-laid as per designed section. Figure 3 shows the treatment of longitudinal cracks at top of dam by trenching, watering and compacting.

After refilling the trench, 3m c/c holes be drilled and grouted with clay bentonite slurry at low pressure if warranted. The holes for grouting are taken upto the level of contact between earthwork and sloping back surface of masonry of wing wall or key as the case may be. On the d/s side, rock toe, and toe drain be opened and cleared upto a length of three times the length of key and then re-laid afresh, as per design section.

Treatment for depression and protrusions on d/s face

In case the depressions and protrusions are small, it would be difficult for the new earth to stick with the existing one because of the problems of preparing the old surface and compacting the new mass. In such cases where the depressions and or protrusions are up to 200 mm or less, the downstream slopes need not be disturbed.

In case the depressions are of larger magnitude, then remove all trees, bushes and harmful vegetation from the depressions and also from the downstream slope. All material in loose pockets should be thoroughly scooped out. All borrow pits, ponds or depressions downstream of the dam and within a distance from the dam toe equal to ten times the head of water should be filled up. Holes made by rodents and other burrowing animals should be carefully located, opened up and refilled with proper earth (not clayey) and properly rammed. Cut the depressions in u/s face to vertical and d/s at normal to slope or about 20^0 as convenient. Moisten the surface. Select fill material, which should be free from tree stumps and organic matter, trash, sod, peat etc. In choosing material for sand and gravel fill, the gravel is the more important component. Prefer a well graded rather than a poorly graded material. It is desirable to confirm by visual inspection with an occasional test of gradation. Put about 30 cm thick layer of fill material in horizontal layers. Compact/ ram the layer either by some pneumatic tamper till its density is about 90 percent of dry density of the material. The thickness after compaction would be about 20 cm. Compact till refusal. Place the second layer and compact it and so on till the depression/cavity is fully packed. Water content should be uniform throughout the layer to be compacted and it should be as close as possible to that content which will result in the maximum densification of the material to be compacted. In general this water content will be slightly less than the optimum water content as determined by Proctor compaction test.

Treatment for sloughing

Treatment for sloughing of downstream face is carried out by removing all undesirable vegetation. Lay pervious blanket or filter buttress on the face and extend up to the toe filter. The existing disturbed pitching on d/s slope was to be re-laid to the designed section for rain protection. Longitudinal cracks observed on downstream slope of dam were excavated in the form of a deep trench having side slope of 0.5:1 keeping the crack in center and bottom width of the trenches as 1.0m. The trenches to be backfilled with selected soils with proper rolling and watering.

Fig.3 Treatment of longitudinal crack at dam top

Treatment for longitudinal cracks

Longitudinal cracks to be excavated in the form of deep trench up to appropriate depth and back filled with selected soils and compacted. Figure 3 shows trenching of cracks, watering, and compacting. A 15 cm thick layer of shell material to be provided on the top surface of the earth dam throughout the length to take care of invisible cracks if any and to prevent infiltration of rainwater. Shallow sinkholes where found to be excavated upto a depth of 0.3 m and backfilled with selected soil and compacted. Rich cement mortar slurry to be poured in the gap between the left bank wing wall and the Non-overflow dam section. Surface cracks in the wing wall are to be repaired with rich cement mortar. Figure 3 shows the treatment of longitudinal crack at the dam crest.

Treatment for longitudinal crack and slip

Where the u/s slope sloughed down, due to longitudinal slips, u/s slope also bulged. Minor cracks observed on the d/s slope. Settlement in the earthwork on the u/s slope and pitching was observed following treatment is to be followed.

To remove all the pitching work and the damaged earth on the up stream; to remove the earthwork in the casing section in benches of 2 to 3m in depth and about 4 to 6m in width to facilitate rolling and watering in stages; to excavate each bench step by step, thus clearing the casing zone of all the cracks. Next to complete the earthwork of the casing zone by taking selected materials from the borrow pit area, backfilling the excavated portion, after proper rolling and watering. Then, after bringing the u/s slope to the original levels, pitching to be duly completed.

Treatment for seepage

Where heavy seepage is noticed, the complete d/s area was to be cleared of the bushes and the foliage growth, particularly the toe drain area. The seepage water shall have to be channelised and suitable compartment created to measure the seepage water by providing adequate V-notches at suitable locations. The seepage was to be properly monitored, particularly, with reference to the reservoir levels. In order to assess the final quantum of seepage and also the zones and the area where the seepage is occurring, whether through the body of the dam or below the foundation levels; the following measures were suggested:

Pizometers may be installed on the d/s and also in the body of the dam. Monitoring of these would indicate the nature of seepage, whether through the foundation or the body of the dam. In case the seepage is mainly in the foundation area, it will be necessary to provide adequate treatment either by restoring to cut off measures to be suitably decided after the seepage details are available. Remedial measures for seepage such as upstream clay blanketing, downstream toe loading etc. may have to be carried out, in case the seepage is found to be excessive and concentrated at a particular location at the downstream toe.

The seepage collected in seepage drain at toe of dam should be measured over a V-notch placed at the exit of the dam. In no case the seepage should be more than acceptable limits. The acceptable rate of seepage of 0.07 liter per second (lps) through earth dam per m of dam length (only the length contributing seepage is to be accounted for). The unacceptable rate of seepage is 0.16 lps.

Strengthening of slopes

If a section needs strengthening or flattening of slopes, this should be done by placing coarse pervious material. On the u/s face rock-fill material may be used, if possible. On the d/s face, if only limited placement is needed, once again it should be done by coarse pervious material. However, if substantial placement is required, the quantity of pervious material required can be reduced by placing a chimney drain connected to horizontal drainage filter blanket and rock toe. Beyond the chimney drain S.P. material can be used. Downstream slope should also be pitched to protect it from rain cuts.

Treatment for liquefaction

Where the dam was damaged severely due to liquefaction, the top layer or more as the case may need to be removed under the dam foundation area. The excavated layer should be replaced by well-compacted semi-pervious material upstream of the cutoff trench, and well graded compacted pervious material downstream of the trench. The cutoff trench should be carried down to the rock or hard sub-surface to provide a positive cutoff. Alternatively, densify the foundation material by hammer driven piles on a 3m hexagonal grid through full depth of the foundation. This could be done through 15cm minimum diameter pipes with flat bottom, which could be extracted and the hole filled back with pea gravel. It will be found convenient to use a flat sliding steel shoe at the pipe bottom, which could be sacrificed. This treatment will have to be done first in a test area and post-treatment N-value compared with those before the treatment. Spacing of the pipe or its diameter could be suitably adjusted to achieve the desired N-value. The SPT values should be aimed at 20 or more, which will be indicative of no further liquefaction. Based on IS: 1893-2002, the recommended N-values are given in Table 1.

Table 1 – N-values with depth

Depth below ground level	$\leq$5m	10m
Minimum acceptable N value, Zone IV and V	15	25
Minimum acceptable N value, Zone III	10	20

Note: For intermediate depths, linear interpolation may be used

Where there are successive slides over the full height of the dam slope, it would be necessary to remove all the disturbed soil material from upper most slip face to the required depth. The cut should be made with a suitable slope towards the downstream slope. The removed portion can then be rebuilt with a homogeneous low permeability soil.

CONCLUSIONS

Based on the soil tests and the pattern of damages (longitudinal and transverse cracks, settlement, and disturbance of the pitching) lead to the firm conclusion, that in several cases, damage to dams was mostly attributed to severe vibration and liquefaction of the sub-soil. The rehabilitation of these dams was taken up in two stages. In Stage I, temporary restoration was carried out to bring the 'repairable' dams back to safety without much change in earth dam section to enable them to store water in monsoon. In Stage II long-term restoration of scheme was carried out with earthquake resistant design, restoration and upgrading all the components of the projects. The paper also presents detail of restoration and rehabilitation procedures adopted. The seismic evaluation of existing earth dam as per the current practices have been carried out and zones of weaknesses, if any, have been identified. Appropriate repair, restoration and retrofitting techniques have been adopted to seismically upgrade the dams to counter the future earthquakes.

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