SAFETY PERSPECTIVE FOR DAM CONSTRUCTION – CASE STUDY OF GARARDA DAM FAILURE

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ABSTRACT

Dams are constructed for the retention of water for power generation, irrigation and supply and for protecting people, land and property from flooding. Failure of any dam poses risks to people and property nearby and the services provided by the embankment. A dam may fail when the loading on it exceeds the resistance against overtopping, internal erosion, slope instability, sliding/ overturning, excessive deformation, etc. To properly describe the causes of dam failures, it is necessary to study the characteristics of dam which have experienced failures. India which has built over 5125 large dams has a good track record on dam safety. The failure rate of small and medium Dams of India mirrors the International rate. This paper examines the causes of failure trends of earthen dams in India and abroad and the likely causes of failure with the objective of improving dam safety by plugging the deficiencies in planning, design and construction practices as was noticed during the examination of Gararda Dam failure in India

1.0 INTRODUCTION

Earth dams for storage and diversion works have been built in India since pre-historic times. A few projects constructed during second and third century A.D in South India are still providing useful services. More than 5000 large dams have been built in India since independence (1947). The total storage potential of the reservoirs is around 225 BCM out of total storage potential of about 400 BCM. It is estimated that another 1500-2000 large dams will be required to achieve the ultimate storage potential to utilize it for socio-economic development of the country, including food security and flood control.

In recent years, dam safety has drawn increasing attention from policy makers, practicing engineers as well as the public. This is because floods resulting from dam failure can lead to devastating disasters with tremendous loss of life and property, especially in densely populated areas. Hence, a robust understanding of the characteristics of dam failures (e.g. failure mode, cause and key influence factors) is needed.

A number of studies have been devoted to investigating dam failures. The International Commission on large dams (ICOLD) has reported statistics of dam failures (ICOLD 1995). Many researchers have also conducted studies on dam failures (Zhang, Xu & Ji, 2007). These studies showed that earth dams have the highest percentage of failure (66%) from over fifty countries (including US, UK, India, and Australia) with US reporting the maximum number of dam failures (70%) out 800 recorded failures. Zhang et. al (2007) compiled a database of 593 worldwide earth dam failures (excluding China), and the study showed that small earth dams with either a small reservoir capacity or a small height appears to have relatively high possibility of failure. Also, it indicated that an earth dam is most likely to fail within its first five years of service, especially during the first year after construction.

Modern well designed dams operated by competent authority fail at a rate of about 10^{-4} per dam-year. In India, 32 dam failures have been recorded so far. Out of which 15 failures have occurred within five years of project completion. The performance of Indian dams thus mirrors the International trends. However, there is a need to reduce the failure rate as the loss here would be more because of high population density.

2. CHARACTERISTICS OF EARTH DAM FAILURES

It is difficult to identify a distinct, single cause for a dam failure. Often, several causes are involved in a failure and these causes are interrelated with each other. Table-1 presents the detailed category of dam failure causes. Table-2 shows the percentages of causes for earth dam failures from 300 reported failures from world over. Most of these failures are caused by either overtopping (36%) or quality problems (43%). Table-3 shows the percentages of sub-causes of quality problems for about 200 earth dam failures. It can be seen that 58% of quality problems are associated with piping in the dam body or foundation. For piping, the most single adverse factor is crack, which is caused by differential settlement, imperfect compaction, material shrinkage, foundation defects and imperfect interface.

Table – 1
Categories of dam failure causes

Sl. No.	Cause	Reason
I.	Overtopping	1. Insufficient spillway capacity 2. Extreme flood exceeding design criteria
II.	Quality problems	1. Piping in dam body 2. Sliding of dam body 3. Piping in foundation 4. Piping around spillway 5. Quality issues in spillway 6. Piping around culvert and other embedded structures 7. Quality issues in culvert and others
III.	Poor Management	1. Decrease of reservoir capacity for flood control due to over storage prior to flood season 2. Poor management and operation 3. Organization issue: nobody responsible for Management of dam 4. Poor construction planning and scheduling
IV.	Disasters	1. Earthquake exceeding design criteria 2. War and Terrorist attack 3. Breaching of upstream dam 4. Rodent den
V.	Others	1. Spillway blockage due to bank slide in reservoir 2. Breach due to excavation on dam for discharging 3. Poor Planning of general layout of project

Table - 2
Percentages of causes for earth dam failures

Sl. No.	Causes of failure	Percentage of dam failures
1.	Overtopping	36.4
2.	Quality problem	42.5
3.	Poor Management	1.3
4.	Disasters	3.0
5.	Others	5.2
6.	Unknown	11.6
	Total	100.0

Table – 3
Percentages of sub causes of quality problems

Sl.No.	Causes of failure	Percentage of dam failures

1.	Piping in dam body/foundation	58.3
2.	Sliding of dam body/foundation	18.3
3.	Piping around spillway	2.8
4.	Quality issues in spillway	6.3
5.	Unknown	14.3
	Total	100.0

3.0 INDIAN SCENARIO ON DAM FAILURES

The main causes of earth dam failures in India are identified as under:-

- Poor project planning
- Poor investigations
- Poor design
- Unsatisfactory location/ site selection
- Faulty or poor construction practices
- Poor construction scheduling, and
- Poor coordination between design and construction units

3.1. Project Planning

The project planning has an important bearing on the satisfactory construction and operation of the project. However, it has been observed that proper project planning is often sacrificed in the garb of economy. Spillways are placed on one side of the project rather than on the main river, no provision is made for Coffer dam construction, no proper construction sequencing is undertaken or chalked out, no construction scheduling is done, no construction sluices are provided. Often it has been found that construction scheduling / sequencing also goes hay ware because of disruption of fund flow. It has been observed that projects often get stopped midway because of drying up of the funds. This results in progress of the project in jerks, which is detrimental to the health of dams and earth dams in particular. The construction in stages, for which no design provision has been made, results in placement of dissimilar materials in an undesirable way, which results in improper bonding. Often it has been observed that a project goes on languishing for years for want of funds. But, suddenly when funds are made available, pressure is put to complete the construction in the shortest possible time to utilize the funds. The required quality control measures are then sacrificed for the sake of achieving higher progress.

3.2. Project Investigation and design

An adequate assessment of geologic and geotechnical conditions of the proposed site is imperative for the safe design and construction. Even though exact assessment is not available, but majority of failures can be linked to geologic and geotechnical problems. Each dam site has its own set of unique geologic and geotechnical challenges. Similarly, the design requirements are different for dams of different size, purpose and hazard potential classification. This makes imperative undertaking of geotechnical investigations and analysis which are site and project specific so as to address the complexity of site conditions and design requirements of the proposed dam project.

Generally States, in India, start more projects than they can fund. As a result, desired funds are not allocated to a given project. The first casualty in such a scenario is the geological investigations and laboratory testing as they are accorded less importance. A limited set of investigations and laboratory investigations are usually undertaken, such as, topographical surveys and some shear strength tests. This results in availability of limited reliable data affecting the soundness of design process. This sometimes leaves certain weakness in the dam or its foundation which can prove detrimental later on. Possible issues that can remain unaddressed are:

- Foundation grouting
- Foundation consolidation / settlement.
- Soil dispersivity
- Moisture control of the placement material

3.3. Project Site Selection

Site selection is crucial in determining two things: (i) the type of dam that can be built and (ii) the value that the dam will present to the society. These factors represent a dam's physical and social viability. The first determining factor is based upon physical and scientific criteria while the second is based upon social, geographic and fiscal analysis.

Physically, the selection of dam site depends upon topography, geotechnical and geological structure of the dam site, availability of construction material, hydrology, seismicity, height of dam, river diversion, etc. However, it has been observed that sometimes, because of absence of any other site or a site has been allocated under cascading development process of a river, the project – found viable on social considerations – is planned for construction at a site which is not viable on physical considerations. In such cases, compromises are made on the technical measures needed for remedying the deficiencies present there, particularly in the case of small and medium projects. Such compromises prove costly and sometimes detrimental later on.

3.4. Project Construction

An examination of the construction practices being followed for small and medium earth dams (and also earth and rock fill dams) shows that they are deficit in one or more of following ways:

a) <u>Construction Planning/ Scheduling</u>
Often it has been found that no proper construction plan or scheduling is done. The construction sequence of different components of the project is arbitrarily selected. The primary objective is to meet the financial targets as fast as possible. This results in construction of high valued items at first such as spillway, gates etc., leaving the construction of earth dam items at the end.

b) <u>Improper construction of closure section</u>
This has been found to be the primary reason for earth dam failures. The construction of closure section is generally undertaken very fast, often in one season. This causes development of high pore water pressures in the foundation and embankment, inducing high consolidation later on. Any high level difference in bed of the closure section may induce differential settlement. Further, if proper precautions are not taken proper bonding between the material of the existing dam section and that of closure section may not get firm resulting in development of transverse cracks at the interface of the closure section with the adjacent section of the already constructed embankment.

c) <u>Improper placement of filter material</u>
The filter material is the safety valve of the embankment dam. Its improper placement will defeat the very purpose of its provision. It has been found that proper procedures are not followed during filter placement and the filter material often gets mixed with the shell/core material. The horizontal filter is highly susceptible to this mixing.This reduces its permeability significantly, and thus the filter fails to perform the intended function.

d) <u>Excess thickness of soil lift and compaction methodology</u>
A lift thickness of 15 cm is generally prescribed after compaction by sheep footed roller (tamping roller). However, it has often been found that lift thickness of 30 to 35 cm and sometimes 50cm is resorted which results in deficient compaction. Also, in some places pneumatic tire rollers are employed. These rollers produce relatively smooth compacted surface, which must be scarified before placing next lift. However, these types of rollers are not effective as sheep foot in breeding down soft rock or in mixing fill material. A higher lift or improper mixing may cause differential settlement leading to hydraulic fracturing. The effectiveness of spreading and processing equipment needs to be assessed through test fills, which is not always adopted.

e) <u>Water Content</u>
The density, permeability, compressibility and strength of impervious and semi-impervious fill materials are dependent upon water content at the time of compaction. Soils that are compacted wet of optimum water content exhibit somewhat plastic type of stress-strain behavior. Alternatively, soils that are compacted dry of optimum water content exhibit more rigid stress-strain behavior. However soils compacted substantially dry of optimum water content may undergo undesirable settlements upon saturation. It has been generally observed that in the field, stress is laid more on achieving the desired density rather than on the appropriate water content for the required density.

Though, higher density can be achieved by putting more compactive effort on soils on dry side of optimum water content, but such a soil would undergo undesirable settlements upon saturation. A combination of such dry of optimum lifts with optimum compacted lifts would cause gaps to form upon saturation leading to piping because of different compaction patterns.

f) <u>Junction between embankment and concrete structures</u>
Special attention must be given to the junction of embankments with concrete structures such as outlet works, spillway walls, locks / retaining walls and power houses to avoid piping along the zones. An embankment abutting a high concrete wall creates a tension zone in the top of the embankment. Such a scenario would require placement of material at higher water contents to ensure a more plastic material which can adjust without cracking, but then the effects of increased pore water pressures must be considered. Further, pneumatic roller may be used for compaction at these interface locations as sheep foot rollers can cause damage to the structures. Where rollers cannot be used because of limited clearance, power tamping of thin layers should be used to obtain densities equal to the remainder of the embankment. However, it has been found that this remains the weak link and proper compaction is often not done. With the result, such junctions become the path for seepage and eventually piping, if filters are also not placed correctly.

g) <u>Junction with abutment areas</u>
In abutment areas, large differential settlements may take place within the embankment, if the abutment slopes are steep or contain discontinuities such as benches or vertical faces. This may induce tension zones or cracking in the upper part of the embankment. It may be necessary to compact soils wet of optimum water content in the upper portion of embankment to eliminate cracking due to differential settlements. However, during construction such a practice is usually not followed.

h) <u>Foundation preparation and cleanup</u>
The foundation preparation is an important activity in embankment dam construction. The dam foundation shall be prepared in accordance with standard guidelines (IS: 11973:1986). Generally, it has been seen that this activity is hurriedly rushed through and fill placement is commenced on improperly prepared foundation. It is difficult to access the foundation preparation done after the fill has been placed. Inadequately prepared foundation strata may undergo differential settlement in case of soil foundation, or would cause flow through joints or piping if it is of rock.

3. 5. Coordination between Design and Construction units

Close coordination between design and construction personnel is necessary to thoroughly orient the construction personnel as to the project design intent. This is accomplished through interaction between the construction engineers and the designers, and by undertaking required visits to the site by the designers. Visits to the site by design personnel are required to ensure the following:

- ➢ Site conditions throughout the construction period are in conformance with design assumptions and principles as well as contract.
- ➢ Project personnel are given assistance in adapting project designs to actual site conditions as they are revealed during construction.
- ➢ Any engineering problems not fully assessed in the original design are observed, evaluated, and appropriate action taken.

4.0 CASE STUDY OF GARARDA EARTHEN DAM (RAJASTHAN)

The Gararda earthen dam is a medium irrigation project on river Mangli, and Doongi and Ganesh Nallahas in Bundi District, Rajasthan. The dam length is 4.271 km and its maximum height is 30m. The work on the dam commenced in the year 2003-2004 and was completed in the year 2008-2009. The reservoir filling commenced on July 26, 2010 and a portion of the dam (closure section) breached on August 15, 2010 when the water level in the reservoir was at El.291.00m (FRL 295.50m).

4.1 Examination of failure

An examination of the project records and site visit undertaken after failure showed that -

a) A homogeneous embankment section was constructed using CL/CI clay material against the zoned dam section designed/proposed.

Fig 1: Homogeneous embankment section

b) Other than preliminary investigations at the feasibility stage, no detailed investigations of the dam foundation and material were carried out.

c) Adequate construction planning of the project was not done. Besides, adequate thought was not given to the planning/viability of dam closure sequence. The dam closure section was completed in a period of three years, instead of one season. Further much steeper side slope of the already constructed embankment sections adjacent to failed section was adopted as against IV: 4H normally adopted. The lift thickness adopted for construction was much thicker than that stipulated in the contract document.

d) No arrangements were made for controlling the reservoir filling rates during initial filling of the reservoir. The depth of water in the reservoir had risen from 0 feet to 46 feet over a period of just 20 days. The maximum rise in any day was of the order of 11 feet. A day before the reported failure, the reservoir had recorded a rise of 6 feet. Even at the time of failure, the reservoir was on rising trend.

e) The dam in the breached portion (also the deepest river bad portion) was found to have been constructed on a jointed/fractural rock mass. Many wide, deep and continuous joints were seen running from upstream to downstream both longitudinal and transverse, covering the whole area of the breached dam section. No sealing of these joints was done, and the foundation cleanup was also not done properly before taking up the earth work.

Fig 2: Breached Section foundation area showing rock joints running continuously from upstream to downstream

f) Filter arrangements were not provided properly. Infact, it was difficult to confirm by visual inspection of the breached section as to whether any chimney filter (vertical/horizontal) has been provided in the dam section.

Fig 3: Breached section showing no visible signs for confirming the presence of chimney filter

g) Deep rain cuts were observed on the downstream side pointing towards improper compaction of the soil used as dam material along the slope.

Fig 4: Downstream slope showing deep rain cuts and excessive weed growth

4.2 Possible causes of failure

It is difficult is to arrive at any definitive cause of failure. However, from the perusal of records and site inspection taken, the following or a combination thereof could be the cause of failure:

a) The foundation of the closure section did not appear to have received the level of preparatory treatment that is typically required. No systematic consolidation/curtain grouting of the rock foundation was done. This was evident from the wide, deep and continuous joints, both with and without fill material, seen running from upstream to downstream. This could have caused washing of the fine material under increasing reservoir head, leading to differential settlements and slope instability.

b) The filters (both horizontal and vertical) perform the important function of reducing the pore water pressure and blocking the migration of clay particles. The filter provided at the closure section and elsewhere did not meet the prescribed specifications as they had got mixed with shell/core material, and thus failed to perform the intended function. Laboratory tests done subsequently showed that the filter had almost become impervious and its permeability was of the order of 1x 10-5 cm/s.

c) The fill in the closure section was reported to have been placed in relatively thick lifts as compared to the specification prescribed. Also, instead of using 7.09 ton sheep foot rollers as originally planned with 15cm thick layers, 43 ton pneumatic rollers were used with 30-40 cm thick layers. This higher compactive effort though achieved the prescribed density (at dry of optimum moisture content) but may have also built a collapse potential into the fill. Such collapse potential develops when a given point within the fill experiences an increase in confining stress over the initial yield stress induced by compaction; and the collapse strains develop if the water content increases subsequently. In case of Gararda dam, fill located immediately above the creek holds the most critical situation – the dam reaches here the maximum height and the seeping waters through the crack bed could easily lead to capillary rise affecting a certain thickness above the original ground level. Therefore, the fill volume having the highest collapse potential is viewed as an elongated mass of compacted soil lying directly above the crack. A collapse of this volume would tend to create voids and cracks, which could lead to a preferential path connecting the upstream and downstream of the dam.

d) The failed section, being the closure section was the last to be taken up for construction whereas the other portion of the dam adjacent to it had been constructed much earlier. This prolonged time gap could result in differential settlements at the interfaces and formation of cavities unless special precautions are taken. No such precautions were seemed to have been taken. The side slopes of the closure section/previously constructed embankment were kept less than 1H: IV as against the requirement of 4H: IV. Also the base of the section was not horizontal. In the longitudinal direction, along the dam axis, portions of the river bed on the right bank were 5-7m higher than the deepest section. Further, the work on the closure section was completed in three working seasons. Sections were taken up at random for construction which appeared to have prevented effective compaction. The staggering of construction and other mentioned induced weaknesses in the section could have induced formation of crack during reservoir filling and consequential seepage/ piping.

e) There were no arrangements to control the rate of reservoir filling. Generally, the reservoir of the earth dam is filled at a very slow rate of the order of 3 feet/day to allow the dam soil to swell to fill up the shrinkage cracks that might have developed during the construction period and also to take care of any other weaknesses that may have been there. However, with the fast reservoir filling encountered in gararda, the soil was perhaps not given the time to swell and fill up those cracks which induced piping.

f) The level of coordination needed between design and construction units was missing. This was evident from the fact that a single drawing of earth dam section was there for the construction of the whole length of dam. Further inputs from geologists were also not taken at any stage during the course of foundation preparation or before taking up the earth work.

The failure through piping/seepage through the foundation gets corroborated from some of the incidents observed prior to failure. These incidents are:

- A pool/pit located at about 30m d/s of the dam toe of the closure section was reported to be always filled to the brim. It was being used by the villages for meeting their water requirements for the past many days prior to dam failure.
- Some cracks were reported to have been developed in the breached section prior to failure. Attempts were perhaps made to stop seepage of flow through these cracks, but were unsuccessful. These cracks could have developed due to differential settlement because of any of the reasons enumerated above.

4.3 Issue of Institutional Capacity

Out of 32 reported failures of dams in India, Rajasthan has recorded maximum failures numbering 11 (about 35% of total failure). This evidently puts a question mark on the institutional capacity of Rajasthan in handling dam safety matter. The examination of Gararda Dam failures underlines some of the critical institutional issues, which is no small measure, has also contributed to the failure of Gararda dam. Such organizational level issues – which go beyond the level of individual omissions and commissions – are summarized below:

a) <u>Need for enhancement in the technical know-how and dam safety awareness</u>
As evident from the proceeding paragraphs, the planning and design of Gararda dam has not been up to the desired level. Even in taking up of construction, the supervisory staffs have indulged in such oversights and mistakes which points to lack of dam safety awareness.

b) <u>Need for improved organizational system and practices</u>

Lack of co-ordination between design and execution units, and absence of geologist's vital inputs in dam foundation matters, indicates weakness in the organisational system. The fact that quality control unit – through involved throughout – has not performed the intended functions, and also the fact that drawings and other records of execution have been inadequate or poorly maintained, highlights the need for development of sound organizational practices for achieving higher dam safety levels.

c) Need for motivating environment and building of organizational learning curve
Fear of an unreasonable punitive action is the foremost de-motivating factor for an organizational system, and it also hinders the organizational capacity to build upon the learning curve. This fear factor incapacitates the concerned staff from correctly responding to an emergency situation – which could save the dam and thereby the lives of hundreds of people – instead of a natural reaction for saving own skins. Moreover, the general tendency for tanning all concerned with the same brush in the event of a failure, often leads to a cohesive and negative behavior on the part affected staff, which hampers correct identification of the factors of failure. Gararda failure incident is reflective of such entrenched behavior which prohibited a clear understanding of the failure mechanism and the underlying reasons, thereby foregoing a chance for building up the organizational learning curve for dam safety.

5.0 CONCLUSIONS:

It can be seen that the failure rate of small and medium dams in India mirrors the International trend. However an improvement in construction practices and coordination amongst the different units/ agencies associated with the project can bring about a dramatic reduction in the failure rate. Following conclusions can aslo be drawn in this regard :

a) The most common causes of earth dam failures are piping in the dam body or foundation and overtopping. The quality control issues are the major cause for piping related failures.

b) A proper planning on dam site selection, project layout, design and construction is essential for safety of dam.

c) Geological investigations and laboratory testing should be considered an essential part of design. Expenditure made towards this shall not be considered as waste; rather it shall be construed as investment for dam safety.

d) The dam foundation preparation and cleanup should be given due importance. Any laxity on this score can prove hazardous later on.

e) The contact surface between the core of the closure section and the existing dam should be appropriately sealed. Also continuity of filters should be ensured.

f) Abrupt changes in geometric configuration or material stiffness in an embankment dam can lead to stress distributions which will greatly facilitate the occurrences of hydraulic separation or hydraulic fracturing. Such abrupt changes should be avoided.

g) It is important to recognize how quickly a dam failure may occur due to internal erosion. For this reason, it is essential to fill the reservoir slowly under fully controlled conditions and to have means available for lowering the water level rapidly if problems develop.

h) There is a need to sensitize the construction/quality control team of the importance of adopting good construction practices for dam safety. There is a general belief that embankment dams are quite resilient and it can absorb any laxity in construction practices. There is a need to change that belief with introduction of good constructions practices.

i) The organizations responsible for construction, operation and maintenance of dam shall being improvements in their organizational capacities for handling dam safety matters.

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