DIAGNOSIS AND RESTORATION OF A DISTRESSED DAM: CASE STUDY OF GUJARAT, INDIA*

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1. INTRODUCTION

Dams are complex structures which sometimes do not manifest the sign of distress explicitly and hence the damage to them becomes irreparable or very difficult to repair unless causative factors are understood. Many times that the diagnosis of the fault becomes an issue as the symptoms are strange which do not allow a trace back to the cause and hence the repairs can not be done timely. Sometime some aspects which required attention at the time of construction are ignored and therefore they do not perform as per expectations or suddenly manifest signs of distress. However, non-recording of such deviations make trace back difficult. Repairs of every dam become a unique case study because of the said reasons. The paper discusses a case study of a dam that exhibited some strange signs in a short period of about 2 years from its completion. In absence of instrumentation the diagnosis became more difficult. Importance of diagnosis is underlined through this case study. The paper also discusses importance of special materials in repairs of dams.

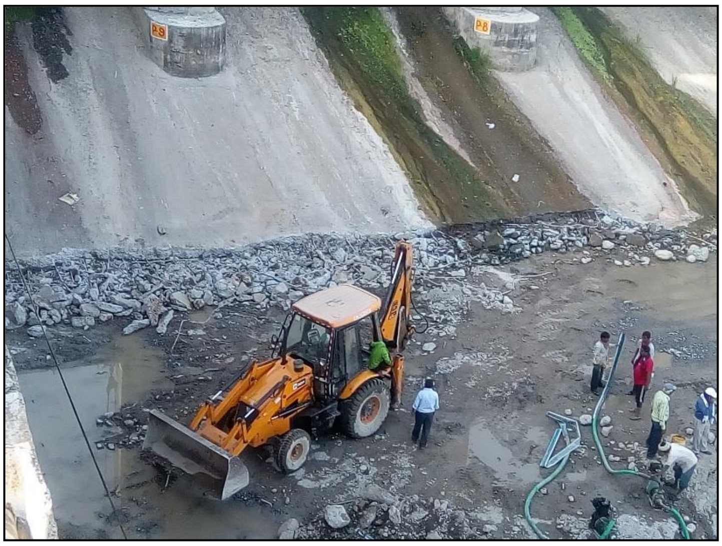

Fig. 1
Pullout of Reinforcement at Toe

An irrigation dam – Gorathiya has been situated in Sabarkantha district i.e. in North Gujarat in India. Its construction was completed before 10 years across river Meshwo. Its Gross Storage Capacity has been 146 Million Cubic Feet. Its catchment area is 371 square Kilometers and the designed flood at the dam site with 1 in 50 year frequency is 3774 cubic meter per second. The storage is small but the spillover capacity is large. Length of the spillway section is 101.80 meter. The concrete gravity dam has been provided 9 vertical gates. Hydraulic jump type stilling basin has been provided in the downstream for energy dissipation. Upstream and downstream keys were 3.5 meter deep.

The Gorathiya dam manifested some signs of distress after only 2 years from its completion. Distress in a new dam was a matter of concern. The downstream glacis slope has been 1:3 whose toe got disintegrated and the reinforcements were pulled out as a sign of distress as shown in Fig. 1. The next year the downstream apron got damaged but not in the entire length of the dam, only in the right half of the length i.e. river's half width as shown in Fig. 2.

Fig. 2
Top View of Pulled Out Reinforcement at Toe and Damaged Apron

The loose concrete was removed from the apron and fresh concreting was done twice but the same problem recurred. Though the apron was reinforced with thick reinforcements, large pieces of concrete were removed during the operation unlike normal behavior of the apron which exhibits scouring damage after some years.

Gate Operation Guidelines for the project provides for opening three gates for 15 cm to allow 15 cumec of discharge initially from when all the gates are closed and then to open two gates on either side to allow 35 cumec discharge in total and then further opening rest of the gates to release 150 cumec. Then the end gates would be opened gradually. Thereafter all the gates would be operated gradually to reach the full designed discharge in total 6 hours of time. The gate operation schedule is designed considering the width of the spill-over section and the condition and profile of the stream in the downstream.

Actual operation of the reservoir has been recorded to have been on the same line. However, maximum damage was found during the initial opening of seven gates and when the discharge was about 150 cumec.

2. DIAGNOSTIC ANALYSIS

Disintegration of concrete at toe of the downstream slope of the dam and pulling out of reinforcement in the entire length at the same location clearly suggested that it was not a construction flaw but it was due to cavity formation during release of water. This was because the glacis with 1:3 slope was insufficient to avoid cavity formation. There should have been a much flatter slope or an ogee. This part of the diagnosis was comparatively easy as it required only inspection and some knowledge of design.

Cavitation has been studied in civil engineering, especially in hydrodynamics, since long back. Formation and collapse of cavities in a stream of flowing water which results from pressure changes within stream by changes in the velocity of flow. Sudden velocity changes generate pressure variations. When the flow is initially released from a reservoir by opening the gates, in some cases, depending up on the slope profile and flow characteristics, there happens such a situation in the downstream between the surface of the falling slope or ogee and the bottom of the flow trajectory. When the pressure becomes very low, sometime negative, it is called cavitation. It generally results in to rupture of concrete under tensile forces due to negative pressure. It may result in to pull-out of reinforcements along with the rupture of concrete if the tensile forces are large.

According to the profile of the fall, trajectory of the water flow and length of the weir from which the water is released, there could be different states of cavities. Pressure variations also form vapor. When the ambient pressure exceeds the vapor pressure, cavities collapse very rapidly and generate high pressures in the vicinity. Sound is also generated when cavities collapse. In some situations collapsing cavities are observed to rebound and go through several cycles of expansion and contraction. Solid surfaces are damaged by pitting when cavities collapse close up against them.

In order to avoid cavitation along the glacis fall, some aeration mechanism like in-between step or a varied slope is provided in some cases. Aeration mechanism allows the air to enter the cavitation to address the issue of pressure drop or to release from high pressure seizure.

The reason for repeated damage in the half of the length of the apron was difficult to understand. If it were a design flaw, the damage would have been in the entire length of the dam. If it were a poor quality concrete in the apron, repeated failure could not be there as the repairs were done meticulously. For some years the reason for the said failure could not be identified. To understand the behavior of the apron, the history of site investigation was thoroughly studied to commence with. There was some record that a shallow basalt mine was in operation in the gorge of the river as the river was having good quality basalt in its bed. For preparation of the site, the design included lean concrete filling with large coarse aggregates i.e. plum concrete in the mining pit over which the dam was constructed. The investigation began with identification of width and depth of the mine. Some other records with geological mapping suggested that the mine was only in the right half width of the river and the depth was about 9 meter. It was a shallow pit formed by removal of basalt from this location which was advised to be filled up with plum concrete. Location of mine located in right half width of the river and failure pattern of the apron gave a sign of co-relationship. To study the foundation in this context became important to make diagnostic analysis.

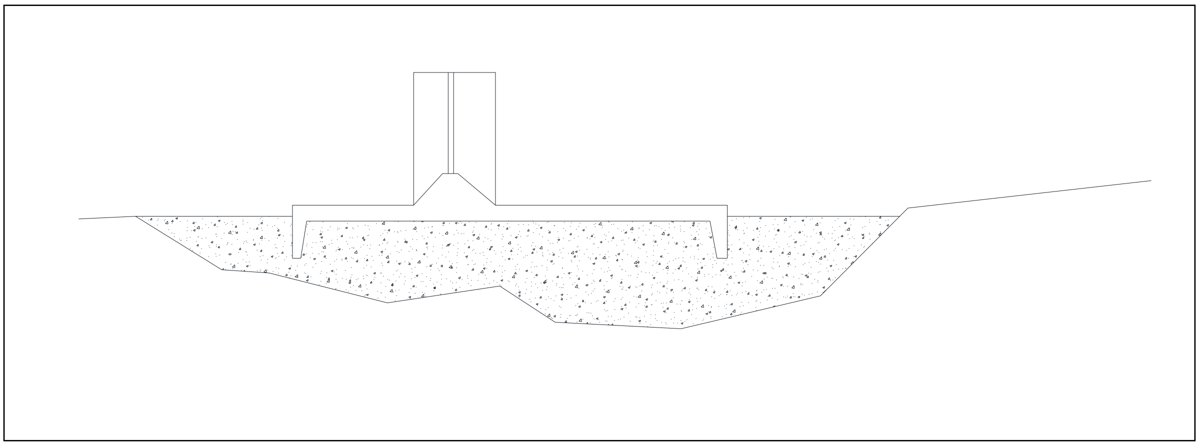

Fig. 3
Schematic Cross Section of Dam and Mining Pit

The apron was removed and the plum concrete beneath was investigated. It was learnt that the large coarse aggregates placed with mechanical locking and no compaction could be done but the cement and sand were in loose form and hence there was substantial amount of water beneath the apron in the voids of the aggregates. The dam was full up to crest level i.e. approximately 6 meter from the bed of the river. The risk of water gushing out from the foundation was also there in the given situation. The scenario on the site gave a clue that the filling of the pit was aimed at plugging it but either the concrete was not allowed to set properly or the compaction was not done properly and hence the concrete had a very loose matrix and hence the voids between the large coarse aggregates were filled up with seepage water from the reservoir in the upstream of the dam. Large coarse aggregates were loosely placed with sand infillings. However, compaction of the concrete was not evidenced. The voids were full of water with a head of about 6 m. There was a clear risk of piping and problem of erosion of plum concrete. The water started flowing out after some hours which corroborated the said finding. This condition was extremely dangerous as at any time the subsurface flow could result in to undermining the foundation and collapse of the concrete dam itself.

The reason for damage to the apron in the right half length of the dam was then understood. When the gates were opened and water was released, the impact of the water fall was supposed to be taken up by the apron which required a solid foundation beneath which actually was not there and hence the concrete apron used to settle which caused sagging resulting in to damage at the bottom and top – bottom damage was not visible but the top was. Thick apron was provided to take the impact but was not designed for large displacement due to loose subgrade causing bending failure. Every time the gates were operated and the apron was found badly damaged due to this situation.

The diagnostic analysis required experience and insight in to the behavior of the dam, spillway, flow of water and its kinetics and of structural behavior of reinforced concrete.

3.0 RESTORATION

The objective of filling the pit with plum concrete was to plug the waterway beneath the apron so as to check the hydraulic path beneath the foundation. Keeping in view the same, plum concrete up to 1.5 meter of depth from the bottom of the apron was removed to see the condition of the plum concrete which was tremendously risky but was somehow done by taking necessary precaution. Albeit, a precaution was taken in the form of a temporary plugging of subsurface waterway beneath the toe of the downstream slope. Cement and sand were mixed in 1:4 proportion with high water cement ratio and it was poured up on the loose material so as to allow it to creep inside the dump of aggregates in the pit and plug it. It was allowed to properly set. Then the initial layer of 1.5 meter which was removed was recast with high cement level and polymers so as to ensure a high strength concrete as the foundation. It was a concrete with normal coarse aggregate so as to ensure proper strength and compaction.

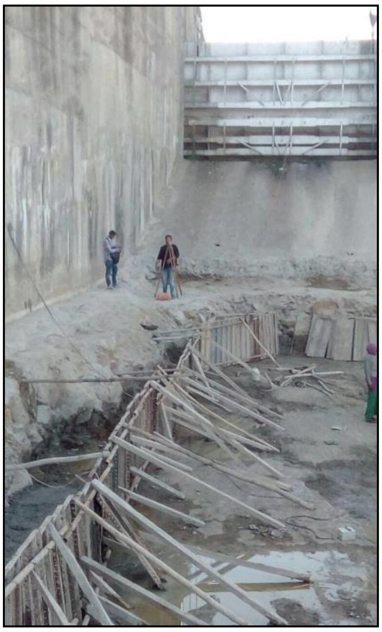

Fig. 4
Construction of Cut-off under Abutment

The apron was to be recast but it was decided to go for a 5 meter downstream cut-off to ensure checking the hydraulic path from the foundation. Additional cut-off was provided with the new apron. The right side abutment was also found vulnerable and hence the shuttering was made at its foundation after opening it and additional cut-off was also constructed there as shown in Fig. 4. A peripheral cut-off was thus provided as shown in Fig. 5. This was to provide a confined solid mass to check hydraulic path and uplift. Entire construction activity required constant dewatering. Rapid hardening agents were added to concrete to ensure early setting of the concrete to reduce the construction time as the risk was very high.

Fig. 5
Construction of Peripheral Cut-off

Removed portion of concrete apron in half of the length of the dam was provided with horizontal and vertical drainage embedded in to the concrete and the new construction of apron was done with properly compacted polymer concrete with reinforcement mesh at the top. These reinforcements were welded with the protecting reinforcements which were pulled out at the toe of the downstream slope of the dam. The concrete was cast for the apron such that at the toe of the dam was made a curved fillet to avoid pullout during the cavity formation. Strong foundation and strong apron with peripheral key checked the hydraulic path beneath the foundation and also assured impact resistance against the fall of water.

Fig. 6
Post-Repair Performance of Dam

It is learnt that generally the concrete apron provided to dissipate energy in the downstream of the dam is subjected to pitting or erosion in many cases. This is because the impact of water is very high and the design engineers provide strong concrete to resist the impact but the property actually required is surface hardness rather than strength. Hardness is tried to be attained by increasing strength in most of the designs but it is found that over some value of strength, much increase in strength is required to have little increase in hardness and hence it is not a cost-effective proposition. Impact resistance was tried to be attained through surface hardening for which was used a special construction chemical on the top of the apron like it is done with the factory floors.

Finally to provide a proper hydraulic condition to the water flowing down, the river channel in the downstream of the dam was remodeled. The entire repairs got completed in a time of four months.

The solution worked out was tested soon i.e. monsoon 2016 and there was full discharge released from the gates twice as shown in Fig. 6 and it was found that the performance was as per expectations. Again during monsoon of 2017 the release was required. The gates were operated in line with the prescribed gate operation methodology. While the maximum damage was earlier observed during initial flow of 150 cumec, no damage occurred during any discharge – 15 cumec onward up to the designed full discharge after restoration.

4.0 CONCLUSION

Problems in civil engineering are very complex and understanding the real cause of the problem is the most important aspect. A small aspect ignored at the construction stage may lead to difficult problems. The diagnostic part in designing the solution of such problems is the most important as that is the key to address the real issue and it needs experience and insight as mostly the findings can be reached by way of using judgmental and intuitive decisions. Therefore, sometime the diagnosis is required to be done stage-wise along with step by step implementation of solution. The solution of such problems may involve several activities to be executed with proper sequence and proper materials. Sometime finer concepts related to properties of material play a crucial role in diagnosis and solution. If proper materials with proper behavioral understanding of different components of the dam are used, long lasting solutions could be worked out.