Repairs of dam components subjected to dynamic loads with application of geosynthetics: case studies from India

Vivek Kapadia
Government of Gujarat, Gandhinagar, India

ABSTRACT: Dam is a complex hydraulic structure having many components subjected to dynamic loads. Such components periodically manifest signs of distress and require repairs especially in case of aging dams. Conventional methods for repairs are mainly based on usage of impact resistant materials. As an alternative, solutions with geosynthetics are designed as impact resistant systems rather than depending merely on material properties. Such solutions not only help effectively repair the damaged components but also enhance their performance in several ways besides cost economy, faster execution and longevous life. The paper outlines main issues related to various dam components due to dynamic loads and presents case studies of aging Indian dams whose distressed components have been restored or are being restored with application of geosynthetics.

1 DAM COMPONENTS SUBJECTED TO DYNAMIC LOADS

1.1 *Upstream face of earthen and rockfill dams*

Waves are generated on the top surface of the reservoir under the effect of the wind. They tend to dislodge the soil particles resulting in to erosion of the earthen dam. As the reservoir level varies, such erosion takes place at different levels of the earthen dam. Such an erosion becomes dangerous when it is progressive. In case of rockfill dams, the wave action may result in to loss of mechanical bond between the adjacent rocks due to penetration of water causing displacement of rocks.

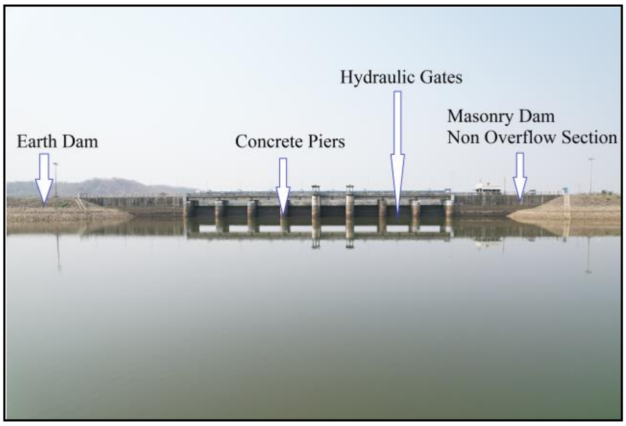

Figure 1. Components of a typical dam - upstream view

1.2 *Upstream and downstream faces of spillways*

Discharge from reservoir is released and regulated through spillway and gates and therefore the crest on its upstream and downstream faces is subjected to severe loading conditions. Under the effect of heavy dynamic water loads, cavity formation on the downstream face is a common problem which may result in to pitting or delamination of the concrete surface. Such forces are so severe in some cases that the reinforced concrete lamination of masonry structure gets disintegrated.

1.3 *Hydraulic gates and supporting structure*

Hydraulic gates and supporting structure resting atop the spillway crest are subjected to heavy dynamic loads as they govern the discharge from over the spillway. Gates are usually made up of steel and they undergo various types of deformations including warping under such loads. The entire system has to take severe vibrations and therefore they undergo fatigue at times. Embedded parts in to concrete elements are of utmost importance and fatigue in concrete members affects them.

1.4 *Energy dissipation portion*

Downstream of the spillway is the energy dissipation portion which is also subjected to high magnitude dynamic loads as its basic function is to dissipate the energy within the falling water and to streamline the flow to the best possible extent. Concrete gets badly distressed in many cases are frequent repairs are usual. In some cases, residual energy in the downstream of the energy dissipation portion is so much so that erosion takes place for a long distance in the riverbed.

1.5 *Power channel and divide bund/ wall*

Dams equipped with hydropower turbines have a divide bund/ wall separating tail race channel of hydropower units and the spillway channel. Conduce hydraulics of the tail race channel is required for efficiency of the hydropower units. Spillway channel streamlines the flood water in to the river gorge. Both these functions are exclusive and hence the divide bund/ wall is designed to ensure distinct hydraulic behavior on either side. It has to take different types of dynamic loads on both of its sides. In some cases, where the divide bund/ wall is not on a straight alignment, it has to act as a river training work. In such cases, it has to take heavy impacts and requires frequent repairs.

2 CASE STUDY OF UKAI DAM: RESTORATION OF DIVIDE BUND

2.1 *Overview of Ukai dam and distress observed in its divide bund*

Ukai dam is located in Gujarat state of India. It was constructed on Tapi river in 1972 with live storage capacity of 6730 million m^3. Total length of the dam is 4926 m of which 4058 m is an earth dam and 868 m is the spillway which is a masonry gravity dam with 22 radial gates whose discharge capacity is 37,865 m^3/s. There are 4 riverbed hydropower turbines of 75 MW each.

Divide bund acts as a groin on the spillway channel side, and, during the spillway operation, it is subjected to severe dynamic loads when it contracts the flow. Here, the original construction was in the form of an earthen bund covered with thick stone pitching. In spite of periodical repairs, signs of serious distress were observed in 2019. Near the hook-shaped nosing (Fig. 2), not only the stone pitching was disintegrated but also the stones were ruptured (Fig. 3) and the surface of the earthen bund was found badly eroded. Riverbed though made up of monolithic basalt rock was found eroded badly to the extent of 5 m in depth and 8 to 10 m in width. Heavy erosion in rocks may cause undesirable changes in hydraulic behavior of flow.

2.2 *Method of estimation of buffeting forces*

While making original design of the divide bund, a three-dimensional laboratory model was used for deciding its alignment and profile which could take care of the impact due to water splashes during release of the flood water from the spillway. In order to fast converge to the right proposition of the model, wave characteristics were captured through a flume model. For this purpose, simple principles of dynamics were used.

$$p = wv^2 \;/\; g \tag{1}$$

where p is pressure at the striking point, w is the weight of unit volume of water and v is the velocity. As shallow water waves are dominant in such cases,

$$v \approx 3.16\sqrt{h} \tag{2}$$

As the surface is inclined and some additional safety is required, design pressure p = 1.7wh was considered. In such a case, the pressure-time diagram for each wave contains a spike representing the primary impact component followed by a well spread secondary pressure component. As the tarin of waves is a series of waves with a short lag during high discharge from the spillway, only the primary impact component is considered and the aggregate impact is estimated for the design purpose considering maximum 7 cycles in a wave train.

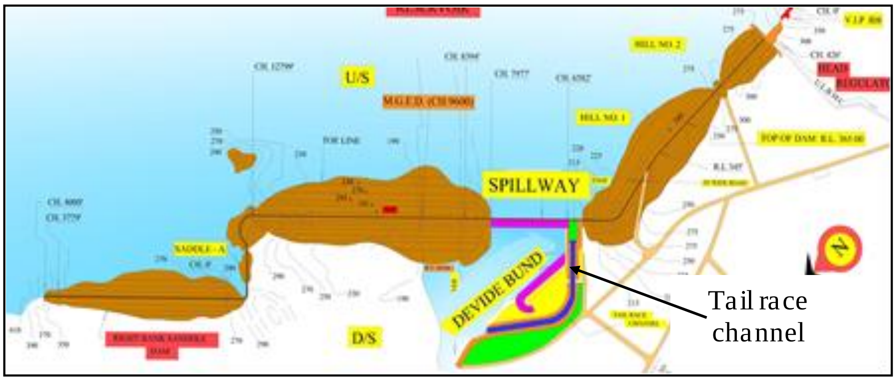

Figure 2. Layout of Ukai dam (Kapadia 2022)

Figure 3. Distressed divide bund (Kapadia 2022)

2.3 *Impact resistant system using geosynthetics and its execution*

Usual practice for protecting earthen bund from impacts due to water waves is to provide a hard surface on it which may be in the form of thick rubble pitching or concrete blocks. Requirement of frequent maintenance of rubble pitching and limitations of compacting techniques to prepare the subgrade suggested that redoing the rubble pitching was not a promising solution. Therefore, as an alternative, a solution was designed in the form of a multilayer impact resistant system using geosynthetics. Three layers – hard, semi-flexible and flexible in sequence from top to bottom were chosen such that stagewise dispersal of impact occurs resulting in to a very low pressure on the earthen bund. Concrete slab as the outer most layer, gabions as the middle layer and biaxial geogrid with tensile strength of 40 kN/m and polypropylene non-woven geotextile as the bottom layer were provided. Filling of eroded riverbed with local rocks near hook-shaped nosing of the divide bund was also done followed by providing a layer of gabions as a lid. The entire system of restoration was designed such that the anti-slide key required at the toe of the divide bund was formed by the filling of the eroded river bed using its existing natural profile (Fig. 4).

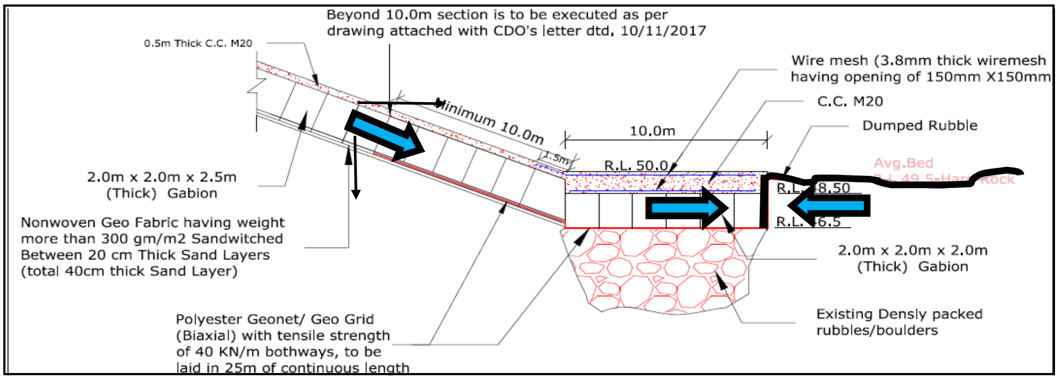

Figure 4. Restoration details - cross section (Kapadia 2022)

2.4 *Performance during floods*

Flood water release for three consecutive years during monsoon has given an opportunity to appraise the effectiveness of the solution. It is observed that the solution has been very effective from hydraulic and structural performance points of view (Fig. 5).

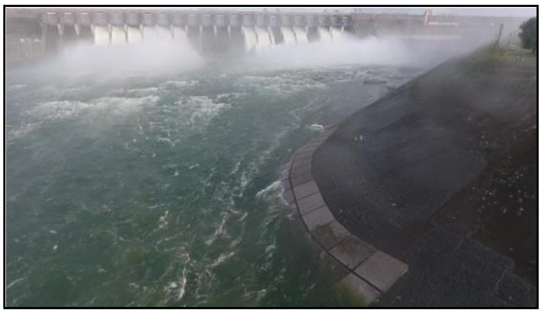

Figure 5. Performance after divide bund after restoration (Kapadia 2022)

3 CASE STUDY OF KADANA DAM: SECONDARY APRON

3.1 *Overview of Kadana dam and distress in energy dissipation portion*

Kadana dam was constructed in 1978 on Mahi River in Gujarat state of India. Its storage capacity is 1542 million m^3. Its main spillway is 406 m long and is constructed of rubble masonry with reinforced concrete lamination. Its design flood is 31,063 m^3/s. Ogee fall height from the crest of the dam is 37 m and energy dissipation is of solid roller bucket type with exposed basalt floor in the downstream. Roller bucket type energy dissipator is preferred when tailwater depth is high (greater than 1.1 times sequent depth preferably 1.2 times sequent depth) and river bed rock is sound (IS7365 2010).

In the solid bucket, all of the flow is directed upward by the bucket lip to create a boil on the water surface and a violent ground roller on the riverbed. The severity of the high boil and the ground roller depends upon tail water depth. Low tail water produces the most violent boils and ground rollers (Peterka 1984). During initial operation of the spillway, such a situation prevails.

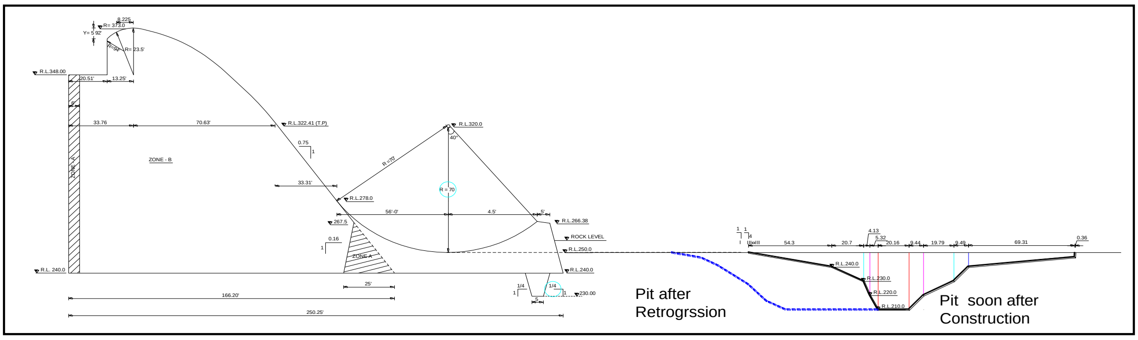

Figure 6. Progressive retrogression of pit in downstream of roller bucket (Kapadia 2020)

Originally, there was a pit in the riverbed approximately 42 m away from the toe of the roller bucket which was not actually that serious as it was away from ground roller and hydraulic jump. However, in 2017 it was observed that the pit that was 12 m deep had undergone retrogression in length but not in depth. The pattern of retrogression suggested that after formation of the surface roller, the balance energy used to be of high magnitude causing erosion of the riverbed. Such issues of riverbed erosion in downstream of the roller bucket are usual and require periodical inspection followed by restoration as per need. Here, it was observed that the change in profile of the riverbed had caused undesirable changes in the hydraulic behavior of the flow.

3.2 *Methodology for estimation of impact on rocky riverbed*

Ground roller occurring on the rocky riverbed followed by hydraulic jump required estimation of impact at the time of designing the dam. Theoretical estimation of impact due to ground roller is not advisable for design purpose in case of a very high ogee spillway and therefore physical model was used.

Hydraulic jump dissipates the energy which can be estimated from the Froud number. Froude number is defined as

$$F = \frac{v}{\sqrt{gy}} \tag{3}$$

where F is the Froude number, v is the velocity of water, y is the height of water and g is the gravitational force. In this case, the Froude number being in range of 2.5 to 4.5, energy dissipation may occur between 20 to 40%. Specific energy before and after the jump is E_1 and E_2.

$$E_1 = y_1 + \frac{v_1^2}{2g} \tag{4}$$

$$E_2 = y_2 + \frac{v_2^2}{2g} \tag{5}$$

where y_1 is the initial depth of water, v_1 is the initial velocity, y_2 is the water depth after jump and v_2 is the velocity after jump. Difference between E_1 and E_2 is the energy dissipated. E_2 in case is too high, the flow tends to scour the riverbed. Pressure on floor at different points can be estimated from the velocity i.e. v = q/y where q is the discharge per unit width and y is the height of the water. During various combinations of gate operations, values obtained from these equations may differ from actual ones, and, therefore, design of the bucket and energy dissipation measures was made using results of physical modeling. Retrogression on the riverbed had altered the hydraulics.

3.3 *Secondary apron using geosynthetics*

Retrogression of the riverbed after long years of operation of the dam required a treatment of the riverbed such that the hydraulics is more congenial and impact is properly resisted. Secondary apron was designed for both these aspects.

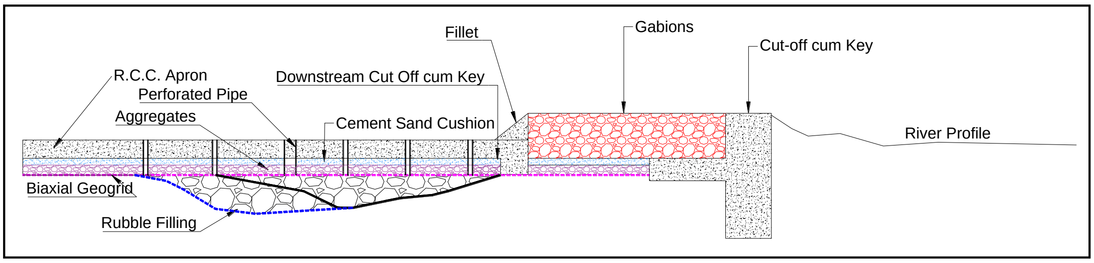

Figure 7. Schematic details of secondary apron as an impact resistant mechanism (Kapadia 2020)

Secondary apron was designed as a multilayer load dispersion system. The top layer of reinforced concrete slab, the middle one a composite layer of coarse aggregate and cement sand mix and the bottom as the biaxial geogrid with tensile strength of 30 kN/m to act as a separator cum basal reinforcement. This entire system was extended to cover the entire pit which was duly filled with graded rubbles. Conventional concrete apron resists impact mainly by its hardness. The solution designed here is a system that takes the impact with sharing its components amongst its members. Thickness of the reinforced concrete apron is required much less than in case of conventional solution because a part of the total impact is taken by it. This results in to a significant cost saving and should give better performance. This solution is in execution stage.

Figure 8. Execution of multistage secondary apron (Kapadia 2020)

4 LEARNINGS AND CONCLUSIONS

Severity of impact depends on stiffness of the material resisting it. Single member impact resistant surface has to take all the impact. Incremental interrelationship between stiffness and severity of impact requires very thick and stiff shield of rubble or concrete in a conventional solution. On the other hand, in multilayer system, impact is shared by the layers, and, therefore, lesser stiffness is required and hence the impact is less severe. Considering long life and importance of dams, application of geosynthetics have a huge scope in their construction and restoration.

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