

Overtopping Protection Systems for Overflow Earth Dams

Omid Pourabdollah, Mohsen Misaghian

Abstract—Overtopping is known as one of the most important reasons for the failure of earth dams. In some cases, it has resulted in heavy damages and losses. Therefore, enhancing the safety of earth dams against overtopping has received much attention in the past four decades. In this paper, at first, the overtopping phenomena and its destructive consequences will be introduced. Then, overtopping failure mechanism of embankments will be described. Finally, different types of protection systems for stabilization of earth dams against overtopping will be presented. These include timber cribs, riprap and gabions, reinforced earth, roller compacted concrete, and the precast concrete blocks.

Keywords—Embankment dam, overtopping, roller compacted concrete, wedge concrete block.

I. INTRODUCTION

EMBANKMENT dams are among the frequent structures used for the water storage. The failure of embankment dams can lead to catastrophic disasters. According to the literature, overtopping was the main cause of embankment dam failures [1]. Hence, different protection systems have been presented for embankment dams to make them safe against overtopping. In this paper, at first, the overtopping failure mechanism will be described. Then, different overtopping protection systems will be reviewed and their pros and cons will be examined.

II. THE FAILURE MECHANISM OF EMBANKMENTS DUE TO OVERTOPPING

Two different failure types may destroy an earth dam during overtopping: surface erosion and/or mass slip.

Surface erosion of downstream slope leads to the breach of dam's body. The erosion begins at the points where the tractive shear stress exceeds the critical resistance keeping the material in its place. For the cohesive soils, the breach happens by the headcutting. The headcut starts from downstream toe and develops to upstream until the dam's crest is breached.

Mass slip is a sudden process. If a proper drainage and filter materials is not embedded in dam, a large pressure field will be created in downstream slope, and in combination with overflow, can lead to mass slip failure of dam.

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III. THE METHODS OF EMBANKMENT OVERTOPPING PROTECTION

In general, there are four different ways to protect earthfills against overflow, including heightening the dam, increase in dam's reservoir capacity, using the fuse plugs, and using the coverage systems. The first three mentioned methods are preventing ways against overtopping. Choosing one of these methods in a specific project depends on various factors, including topography, geology, level of risk in downstream, and economic issues. The most important disadvantage of preventing methods is that they are usually uneconomical, while coverage systems are not only cost-effective, but also can be utilized as spillway, thus enhancing the capacity of existing spillways.

IV. COVERAGE OVERTOPPING PROTECTION SYSTEMS

The coverage systems have been extensively used in recent years, especially in Australia and USA. Some important kinds of these systems are: pre-cast concrete blocks, roller compacted concrete (RCC), vegetation and timber cribs, riprap, gabions, and reinforced earth. In addition to overtopping protecting, the coverage systems have some other advantages. These include utilizing as spillway, energy dissipation, using in diversion dams, and delaying dam destruction. The coverage systems will be introduced in following sections.

A. Vegetation and Timber Cribs

Vegetation is one of the first methods of overtopping protection. It can stand against overflows with maximum velocity of 1.5 m/s [2]. Timber cribs were used in Russia since the 18th century. This system does not have enough strength against heavy overflows. However, it is still used in small levees [3]. Fig. 1 shows the combination of these two systems, used in Australia.



Fig. 1 Greenup timber crib weir [3]

B. Reinforced Earth

The reinforced earth stepped overflow was used for the first time in Prins dam in South Africa in 1920. This system has been used in about 50 projects, most of them were small dams and levees [4]. Fig. 2 shows schematic of reinforced earth used in Toonumba dam. In this dam, the sloping bars were applied to prevent the destruction of upper rocks. A surface mesh was also used to prevent the movement of fine materials.

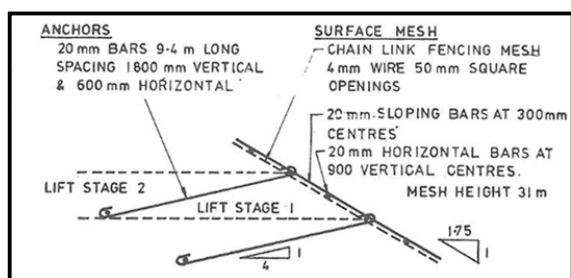


Fig. 2 Reinforced earth stepped overflow in Toonumba dam [4]

C. Riprap

Riprap is made up of rubble stones and rocks with proper size and granulometry. Though riprap is among the most cost-effective overflows, it is not adequately safe against overtopping. United States Bureau of Reclamation (USBR) and Colorado State University (CSU) conducted some experimental tests on ripraps and observed some instabilities during overtopping [5]. The riprap resistance against overflow depends on the material properties, hydraulic gradient, slope of dam and the overflow discharge rate. The design of riprap is based on the mass median diameter (d_{50}) of rocks. The riprap thickness can be considered 1.5 to 3 times the d_{50} . The rounded rocks are more appropriate to use in ripraps. It should be noted that the stability factor of riprap has an inverse relationship with the coefficient of uniformity (C_u). Besides, the poorly-graded materials are more resistant to overtopping, although they suddenly destroy [2].

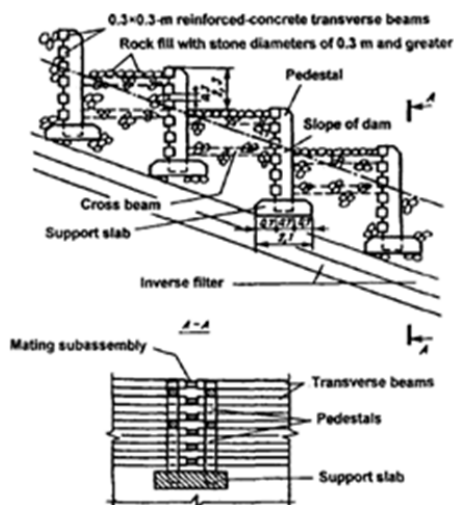


Fig. 3 Design of reinforcement of downstream slope of overflow earth dam

The rocks can be used with concrete and steel. As can be seen in Fig. 3, the rocks are deployed on the concrete slabs and anchored to the dam's body by pedestals. Nevertheless, this method may be only suitable for small dams [6].

D. Gabion

Gabion has a maximum discharge capacity of $40 \frac{m^2}{s}$ [4]. Fig. 4 shows the cylindrical gabions with the size of 940x2400 mm (diameter x length) used in the downstream slope of the Murchison cofferdam.

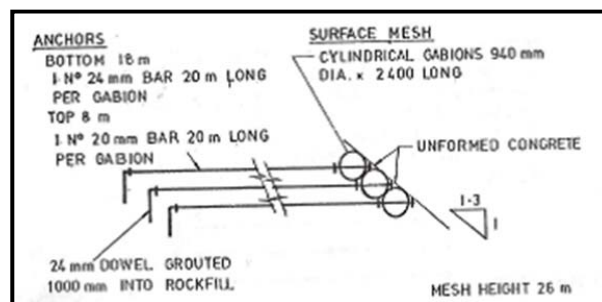


Fig. 4 Downstream protection of Murchison cofferdam using gabions [4]

E. Pre-Cast Concrete Blocks

Reinforced concrete blocks were initially used for overtopping protection. But the investigation showed that the pressure fluctuations of turbulent flow lead to instability of the blocks. Thus, it was recommended to overlap the elements or to use wedge-shape blocks [2].

The idea of using wedge-shape blocks as crest spillway for embankment dams was presented by professor Gordienko in the early 70s in former Soviet Union [7]. Using this system, an overflow with discharge of $60 \frac{m^2}{s}$ and velocity of $23 \frac{m}{s}$ passed over an earth dam without damage to the dam's body. Next studies have been done by Pravdivets [8] to diminish the shortages of Gordienko's design. Five overflow embankments were constructed in Moscow and experimented under overflow discharge of $5 \frac{m^2}{s}$. Out of Russia, the experiments on the large-scale models have been done in England and United States. In 1988, Construction Industry Research and Information Association (CIRIA) in cooperation with University of Salford tried to develop this system [9].

Development of the next studies in England led to the publication of the CIRIA guide for the design of stepped-block spillways. The stepped spillway on the Brushes Clough dam (Fig. 5) in England was constructed according to this guideline. This spillway was built on the downstream slope (1V:3H) to increase the capacity of existing spillway. Its maximum discharge capacity was $3.66 \frac{m^3}{s}$ [10].

USBR in cooperation with CSU performed experimental study on the flume with different step shapes to achieve best design in real scale [11]. One of the most recent applications of wedge-shape block spillways was in the Barriga rockfill dam

in Spain (Fig. 6). On its downstream slope, USBR precast blocks were used to construct the service spillway well-suited for maximum discharge of $7.3 \frac{m^2}{s}$ [12].



Fig. 5 Wedge concrete block spillway on the Brushes Clough dam [3]



Fig. 6 Wedge-shape concrete block spillway of Barriga dam

The most recent studies regarding the hydraulics of flow over the wedge-shape concrete block spillways have been performed by Relvas and Pinheiro, including the inception point and air concentration of the flow, hydrodynamic pressures on the blocks and finally the distribution of velocity as well as the rate of energy dissipation along the steps [13]-[15]. In another recent study, Sabbagh and Misaghian [16] investigated the influence of the flow infiltration through the wedge-shape concrete block spillways on the downstream slope stability of the earth overflow dams using finite element modelling. Their findings showed that if the shell materials with appropriate permeability coefficient are not chosen, the stability of downstream slope will be significantly reduced and thus, the wedge-shape concrete block spillways will be unable to safe the dam for all the overtopping duration.

F. Roller Compacted Concrete (RCC)

RCC has attracted much attention since Late 70's especially in USA. Until the mid-80s, this system has been used as overtopping protection/spillway in more than 100 dams in USA with the height of 4.6 to 33.5 m [17], [18]. Fig.

7 represents Tholocco Lake dam in USA with RCC system.



Fig. 7 RCC stepped spillway/overtopping protection of the Tholocco Lake dam [19]

Brownwood County Club dam is another sample built in Texas, USA in 1939. In the next years, because of probability of flood event with intensity of $330 \frac{m^3}{s}$, it became necessary to add a new spillway to increase the reservoir discharge capacity. For this purpose, RCC stepped spillway constructed on downstream slope in 1984. The project was very low-budget and done in just two weeks. The discharge capacity of spillway increased 350% and it was overflowed six times with no damage (Fig. 8) [20].



Fig. 8 RCC stepped spillway of Brownwood County Club dam after 6 times of overtopping.

One of the main differences between RCC and wedge-shape concrete block is its low permeability. The laboratory test results reveal that the permeability coefficient of RCC mass is $72e^{-12} \frac{m}{s}$ [21]. This characteristic makes this system capable to pass overflow for a long time without considerable water infiltration to the downstream slope.

There are no mathematical or analytical relationships for design of RCC protection and it is mainly based on the construction conditions. It must have proper weight, continuity and durability for resisting against erosion, weathering and movements [17]. RCC is placed on the downstream slope from toe to crest in layers with thickness from 0.3 to .6 m and with minimum width of 2.5 m (Fig 9). To protect RCC, it is possible to place a layer of ordinary

concrete on its surface [20].

Using suitable drainage system underneath the layers is essential. It releases pore pressures, preventing the separation of RCC layer [3]. It is also of importance to completely seal the dam's crest. Considering these issues will prevent the erosion of underneath materials. For instance, in Mt. Carmel dam, the underneath material of concrete spillway located on the left abutment was eroded due to unproper sealing [22].

The guideline of design of RCC protection system which is provided by Portland Cement Association [23] introduces a sample of overflow embankment dam with RCC spillway as shown in Fig. 10. As can be seen in this figure, a safe design of RCC overtopping protection system must include a proper drainage/filter system, an approach apron which is resistance to erosion (2 or 3 RCC layers), and an upstream cut-off wall.

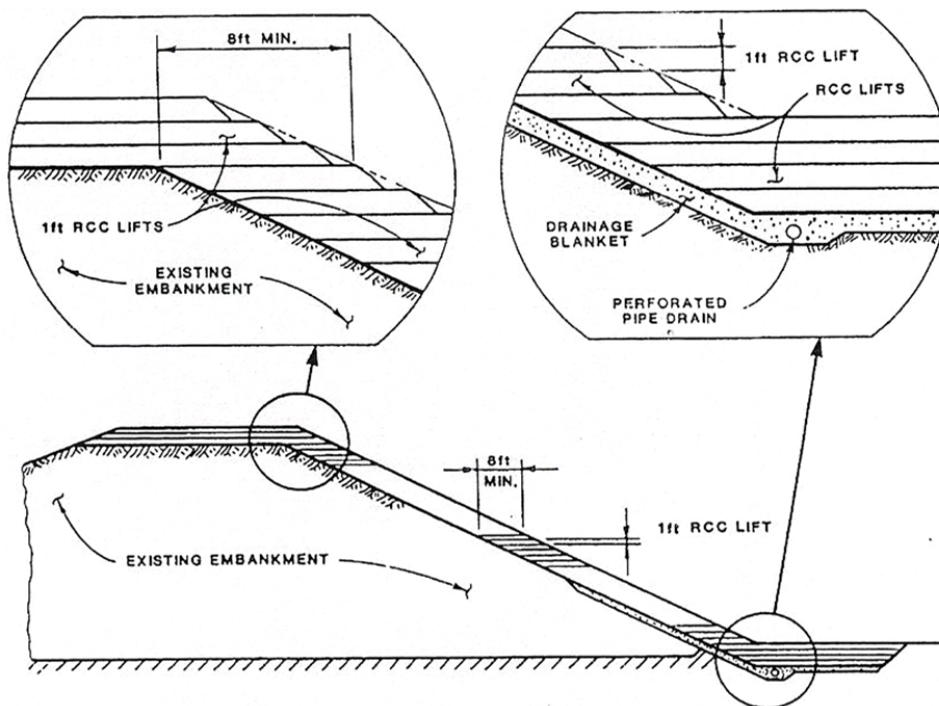


Fig. 9 Construction details of RCC stepped spillway [20]

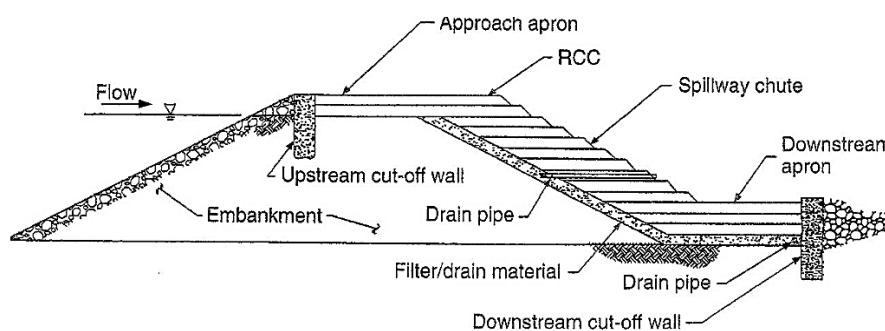


Fig. 10 Typical section of RCC overtopping protection/spillway [18]

V. CONCLUSION

The design flood of a number of dams has been re-examined in recent years, and the calculation results for most of them were more than the initial values used for design of dam. In several cases, occurrence of revised design floods could lead to overtopping. Therefore, different overtopping protection systems have been developed. Choosing the type of system depends on economic issues, the geometry on location of dam, the capacity existing spillway, and the revised design flood. In most cases, considering safety and

economic aspects, concrete stepped spillways would be preferred to other systems. However, according to the past experiences, a well design, proper flow conditions, a good construction quality, and regular maintenance are necessary to provide a safe operation.

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