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Performance of RCC Used for Overtopping Protection and Spillways

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ABSTRACT

Roller-compacted concrete (RCC) has become the most widely accepted method for providing safe overtopping protection for embankment dams in the United States. The concept consists of placing horizontal layers of erosion resistant RCC on the downstream slope of existing dams to increase spillway capacity during extreme rainfall events. Since the first earth dam with an RCC overlay was constructed in 1984, more than 130 such projects have been put in service.

Because most of these hydraulic upgrades were designed to accommodate rare flow events, there was little information initially available of their actual performance when overtopped. With more RCC overtopping protection in service, there are now more examples of floods in excess of the 1 in 100 year event overtopping RCC protected dams. This paper will present data on the performance of RCC overlay projects when overtopped and lessons learned from these actual examples.

Keywords: *Roller-Compacted Concrete (RCC), Overtopping, Protection, Spillways.*

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1. INTRODUCTION

Many older dams in the United States have been determined to be hydraulically deficient because they are unable to safely pass the required design flood without overtopping the dam. In many cases, the required design spillway capacity has increased since the dam was originally designed. This is due to changes in the Probable Maximum Flood (PMF) and/or an increase in hazard classification. The increase in hazard classification is typically due to development downstream after the dam was built which places more people at risk in case of a dam failure.

The overtopping of earth embankments may result in serious erosion and possible ultimate failure depending on a number of factors. They include duration of the flow, depth of overtopping, slope of the downstream flow surface, and the erosion resistance of materials on the downstream face.

While there are a number of overtopping protection measures available to the design engineer, the use of RCC overtopping protection has proven to be the most universally accepted. This is because it is (1) easy to design, (2) easy to build, (3) is non-proprietary, (4) does not change the flow regime, (5) can withstand turbulent flow, and (6) is performance tested as noted in this paper. The only major disadvantage is the no-slump RCC may not have adequate freeze-thaw (F/T) resistance, resulting in some surface deterioration.

Since the use of an RCC overlay to provide increased spillway capacity for an existing earth embankment was first used more than 30 years ago, this concept has been applied to more than 130 dams in the USA. This includes the upgrading of some existing auxiliary spillways with RCC. The dams to which RCC overtopping protection has been applied are generally small dams ranging in height from 15 to 65 feet with most projects requiring less than 5,000 cubic yards of RCC. The highest dam to which a downstream RCC overlay has been applied is 114 feet high and the largest RCC volume on an overtopping spillway project is 160,000 cubic yards. There are two instances where the maximum design height of overtopping exceeds 20 feet under PMF conditions.

Several references have been written on the design and construction of RCC overtopping protection and spillways. The most comprehensive are by McLean and Hansen (1993), a design manual published by the Portland Cement Association (2002), Hansen and Campbell (2006), and Chapter 2 of the FEMA Overtopping Protection Manuel (2014).

2. OVERTOPPING PERFORMANCE – MORE FREQUENT FLOWS

Most RCC overtopping protection projects were designed to accommodate infrequent flood events, usually with a frequency of 1 in 100 years or greater. It was not until recently that several projects were subjected to one of these rare flood events. These examples are covered later in this paper.

However, there are several projects that have experienced overtopping on a more frequent basis. What happened and what was learned from these situations is presented herein.

2.1. Ocoee No. 2 Dam – Tennessee

Ocoee Dam No. 2 is a rock-filled timber crib dam that is part of a hydroelectric scheme built by the Tennessee Valley Authority (TVA) in 1913. It diverts water into a wooden flume that carries water to the dam's powerhouse, five miles downstream.

The 27-foot high dam was modified in 1980 to accommodate white water rafting companies. RCC was placed on the downstream slope in a stair-stepped fashion over some rock infill to allow the dam to be intentionally overtopped. See Figure 1 for a typical cross section of the modified dam.

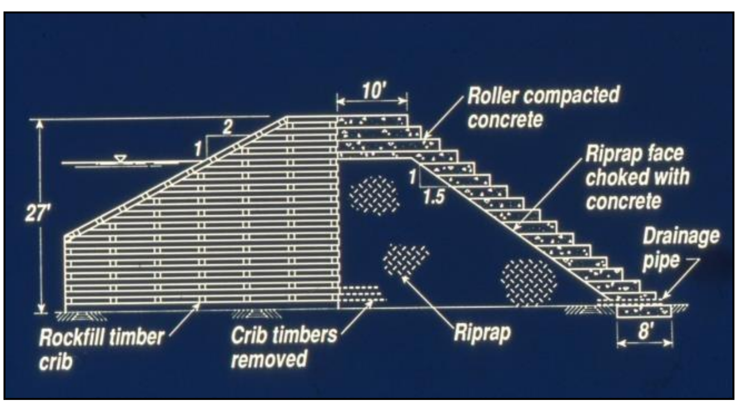

Figure 1. Ocoee No. 2 Dam, TN – Typical Section and Flow Over RCC Protection

The dam has been overtopped from 82 to 116 times per year on many weekends from 6 to 10 hours per day. So, instead of producing hydroelectric power, the dam has now been turned into a recreational benefit. The rafting companies pay TVA for lost power revenue from rafting tickets sold.

Therefore Ocoee No. 2 Dam has now been intentionally overtopped more than 3000 times with no apparent distress to the RCC. Most of the time, the depth of overflow has been about 1-foot, or less. However, during a flood in 1990, it was overtopped by a maximum of 12 feet. See Figure 2 for the condition of the downstream slope after 25 years of service as well as drains at the toe of the dam flowing.

Figure 2. Ocoee No. 2 Dam, TN – After More Than 3,000 Intentional Overtoppings

2.2. Brownwood Country Club Dam – Texas

The first earth dam to receive an RCC overlay to increase spillway capacity was a dam at the Brownwood Country Club golf course. The RCC overtopping protection increased the spillway width from 65 feet to 300 feet and in the process increased the spillway capacity form 2,600 cfs to 11,600 cfs. A typical section of the dam is shown in Figure 3 which was designed for a maximum depth of overflow of 5.5 feet.

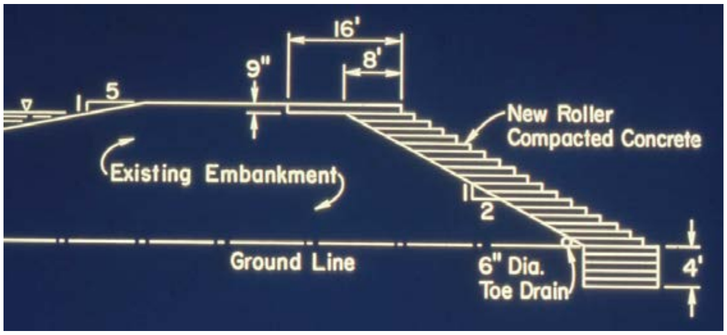

Figure 3. Brownwood Country Club Dam, TX – Typical Section

Figure 4. Brownwood Country Club Dam, TX – After Seven Years in Service

The RCC protected embankment was overtopped six times during its first year of operation to a maximum depth of about one foot. It has been reported that the dam has been overtopped from 1 to 2 times a year since then with a maximum depth of overflow at 2 feet. See Figure 4 for the condition of the exposed RCC which had received no special downstream edge treatment after seven years.

2.3. Lake Tholocco Dam – Alabama

Lake Tholocco Dam is a 45 foot high earth embankment located on Ft. Rucker near Dothan in southern Alabama. It was constructed by the Civilian Conservation Corps (CCC) during the Great Depression of the 1930s. Since that time, the dam has been subjected to high intensity rainfalls from tropical storms originating in the Gulf of Mexico.

The unlined auxiliary spillway on the right abutment failed twice in the 1990s. The first failure occurred in 1990 when a tropical storms dumped 14.5 inches of rain on the site in five hours. After repairs were made to the breached area, the auxiliary spillway failed again in 1994. Once again, this caused complete loss of the reservoir as the flood waters exceeded the capacity of the two spillways and quickly eroded the control section of the auxiliary spillway.

The reservoir remained empty until year 2000 when the Mobile District of the Corps of Engineers designed a 1,550 foot long RCC stepped overlay on the relatively flat 6H:1V downstream embankment sloop. The remediation was designed to overtop with a frequency of one to two years with maximum depth of overflow of 6.5 feet.

The RCC overtopping protection was first tested in September of 2004 when it experienced an estimated flow depth of 3 feet due to Hurricane Ivan and again in March 2005 when it overtopped by 1.5 feet. (See Figure 5). The condition of the RCC steps in 2014 after about ten overtoppings is shown in Figure 6. It has been observed to be in excellent condition with only a slight polishing of the RCC surface.

Figure 5. Lake Tholocco Dam, AL – During Overtopping

Figure 6. Lake Tholocco Dam, AL – Condition of Steps 2014

3. OVERTOPPING PERFORMANCE – INFREQUENT FLOOD EVENTS

After the Brownwood Country Club Dam in Texas received an RCC overlay to increase spillway capacity, it took 25 years before a storm in excess of the 100 year event tested the RCC overtopping protection. The projects described below include four dams in Gwinnett County, Georgia that overtopped in 2009, two dams near Boulder, Colorado that overtopped in 2013, and a rare hydrologic event in the Las Vegas, Nevada area that caused overtopping of an RCC inlet structure at a large detention basin, also in 2013.

3.1. The 2009 Floods in Georgia

In Gwinnett County northeast of Atlanta, seven days of near steady rain produced a rainfall event that exceeded the one in 100 year storm. In one case northeast of Atlanta, the rain exceeded 20.7 inches in 24 hours (50 percent of the PMP – Probable Maximum Precipitation).

Four dams in the Upper Yellow River watershed in Gwinnett County had received an RCC overtopping protection overlay between 2003 and 2008. The dams which had been originally designed by the Soil Conservation Service (now NRCS) had been upgraded in hazard classification due to extensive housing developments downstream. The dams are conveniently denoted as Y14, Y15, Y16, and Y17 by Gwinnett County.

All four dams were overtopped starting on September 21, 2009. During this event, rainfall in most of the watershed exceeded 10 inches in 24 hours. The overtopping of these structures is significant due to the variations in design. In one case, the RCC is exposed, but in the other three cases the RCC was overlain with a soil/grass cover for aesthetic reasons. The spillway discharge coefficients varied as the crest control included a broad crested weir, a sharp crested weir, and two ogee weirs. In addition, in two cases, the auxiliary spillway had parallel training walls and in two cases the spillway converged slightly. All these dams had pipe conduits as their primary spillways.

3.1.1. Y14 Dam (2003) – Date of Rehab

The Y14 Dam with a maximum height of 39.5 feet was designed to accommodate the full PMF flow and would start overtopping due to the 100-year flood. The structure had an ogee crest for the converging stepped and exposed RCC chute that was curved in plan. See Figure 7.

Figure 7. Y14 Dam, GA – Before Overtopping

Figure 8. Y14 Dam, GA – During Overtopping

Y14 was overtopped for up to 30 hours with a maximum depth of overflow of 1.9 feet as shown in Figure 8. Following the overtopping, the RCC stepped surfaces were described as having a slight polish, but no significant damage to the RCC was reported.

3.1.2. Y17 Dam (2005)

The 30-foot high Y17 Dam also had an ogee shape for crest control for its straight RCC stepped chute. The spillway had multiple crest elevations, so the lowest stage would overtop during a 25-year storm event, then the second stage would flow at approximately the 50-year event and finally the one in 100 year would begin to flow over the third stage. It is located in a park and thus had a soil-grass cover.

The Y-17 structure was also overtopped for nearly 30 hours with a maximum depth of flow of 1.2 feet over the highest crest elevation surveyed by the high water mark. This corresponded to a peak discharge of about 800 cfs and unit discharge of 4 cfs/foot. The structure performed as designed with no apparent distress noted. See Figure 9 for the Y-17 spillway operating.

Figure 9. Y17 Dam, GA – During Overtopping

Figure 10. Y16 Dam, GA – After Overtopping

3.1.3. Y15 and Y16 Dams (2008)

These two dams were bid as one package although designed by two different engineering firms. Y15 is the larger of the two dams with a maximum height of 41 feet compared to 34 feet for Y16. For Y15, the crest control is that of a broad crested weir transitioning to an RCC spillway with some conveyance near the abutments. For Y16, the crest control for the straight RCC spillway designed for 0.5 PMF is that of a sharp crested weir to increase its discharge coefficient. Both had a soil-grass cover for the RCC and both had a two-stage spillway to accommodate the 25-year flow first and then the 100-year.

Y15 was overtopped for 30 hours by maximum depth of overflow of about 2.75 feet while Y16 only overtopped for 14 hours. The erosion of the soil/grass cover was quite different for each dam. For Y16, the flow eroded the entire cover over the RCC, as shown in Figure 10, while only a portion of the cover was washed away as shown in Figure 11 for Y15. In each case, the soil and grass that was washed down the steps did not produce any clogging of the stream channel downstream.

Figure 11. Y15 Dam, GA – After Overtopping

3.1.4. Summary of Overtopping for the Four Dams in Georgia

All of the four dams that were overtopped performed exceptionally well and behaved consistent with the designer's intent. The RCC upgraded dams lessened flooding downstream. This was despite the fact that the maximum depth of flow in the downstream channels ranged from 6 to 15 feet.

Following the overtoppings, the grass covers for three of the dams were restored at a minimal cost compared to that needed to repair flood damaged roads and bridges in the county. In April 2010, the stilling basins for each dam were dewatered and inspected for damage. No damage to the stilling basins was noted nor any scour holes downstream of the stilling basins' end sills. However, riprap downstream of Y15 had been displaced.

A post event analysis by Golder Associates indicated that the Y15 and Y17 dams would have failed if they had not received RCC overtopping protection.

3.2. The 2013 Floods in Boulder, Colorado

Rains in the Boulder, Colorado area started on Monday, September 9, 2013 and continued for five days. Nearly 15 inches of rain was recorded during this time with the rainfall peaking on Thursday, September 12 when 9.03 inches were recorded on gauge near Boulder in 24 hours. This record amount of rain was reported in the press as a 1000-year rainfall that produced a 1 in 100 year flow in many areas.

3.2.1. Left Hand Valley Dam

For this 45-foot high embankment dam completed in 1952 with a 2.25H:1.0V downstream slope, the flow event was estimated as a 1 in 500 year flood or greater. The flood coming down Left Hand Canyon from the mountains northwest of Boulder was reported to have peaked at 4000 cfs.

The primary spillway which is located at the right abutment started to spill just before noon on Friday, September 13, 2013. The RCC protected auxiliary spillway whose crest is six inches higher than the principal spillway started to overtop that night. Flow continued over the RCC surface for a week which is the longest duration of overflow for an RCC protection project subjected to an extreme rainfall event. See Figure 12.

Figure 12. Left Hand Valley Dam, CO – During Overtopping

Figure 13. Left Hand Valley Dam, CO – After Overtopping

At the time of the overflow, the stepped RCC surface had been subjected to some freeze-thaw (F/T) deterioration for 15 winters. These cycles of expansion and contraction produced some loose aggregate on the RCC surface of the dam's auxiliary spillway.

The water that overtopped the structure to a maximum estimated depth of 8-inches contained silt, portion of trees, and F/T loosened aggregate. The aggregate laden water caused some erosion of RCC steps with more erosion noticed in the lower portion of spillway. The latter was due to greater amounts of loose aggregate picked up as the overflow bounced down the RCC steps. See Figure 13 for the piles of aggregate deposited at the toe of the spillway. The amount of aggregate was estimated as 10 cubic yards out of the 4920 cubic yards of RCC placed initially.

The RCC was designed to achieve a maximum compressive strength of 2000 psi in 28 days and contained 325 lbs. of cement per cubic yard. The maximum horizontal erosion of the RCC steps which occurred in only a few places appeared to be about 6-inches. Still, there remains about 7 feet – 6 in. of RCC in the horizontal direction.

Following the overflow, the RCC steps are not very pretty. But then, they were not very pretty before the flooding either. In summary the RCC overlay of the auxiliary spillway performed as designed including the drains operating when subjected to overtopping for a week due to a 500 year flood or greater.

3.2.2. Leyden Dam

Leyden Dam is a 43-foot high embankment located in a residential area in Arvada, Colorado, a suburb of Denver. Leyden dam differs from Left Hand Valley Dam in that the principal spillway is a conduit with limited capacity.

The crest control for the RCC armored spillway at Leyden Dam is a concrete sharp crested weir compared to the broad crested weir of RCC for the Left Hand Valley Dam. The strength of the RCC is greater at Leyden Dam due to an increase in cement content to 425 lbs./cu. yd. for the RCC. In addition, Leyden Dam was exposed to three years less of winter F/T exposure and had a higher degree of compaction to the outer edges of its RCC steps.

Because Leyden Dam is located further away from the greatest amount of rainfall that occurred, it was overtopped by a lesser frequency storm for about two days. Still, the overtopping event was greater than the 100 year storm. See Figure 14 for Leyden Dam overtopping.

Figure 14. Leyden Dam, CO
– During Overtopping

Figure 15. Leyden Dam, CO
– After Overtopping

Similar to Left Hand Valley Dam, F/T loosened aggregate was washed down the steps to the toe of the dam as shown in Figure 15. Once again, the RCC protected auxiliary spillway performed as designed when subjected to a 1 in 100 year overflow. Its appearance is better than that of Left Hand Valley Dam before and after the overtopping.

Due to the overtopping of Leyden Dam, the only real damage occurred downstream on Indiana Street, an arterial roadway. At this location, the overflow exceeded the capacity of the culverts under the street and in the process washed away some of the asphalt pavement in this area. The Colorado DOT installed three conduits under the street that increased the pipes' capacity six fold and replaced the pavement in the area.

According to the Arvada City officials, the improvements to the dam minimized damages to homes and businesses downstream.

3.3. Flood Control at Las Vegas, Nevada

Despite an average annual rainfall of only 4.19 inches, considerable flooding has occurred in the Las Vegas area. In order to control sporadic high intensity rainfall events, the Clark County Regional Flood Control District (CCRFCD) has constructed more than 50 detention basins and other flood control facilities. Most of the larger capacity detention basins have RCC over the embankment spillways for these dams. The RCC overlays differ from RCC overtopping protection in that, the RCC is applied to a new structure rather than an existing dam to increase spillway capacity.

3.3.1. The August 25, 2013 Flash Flood

In the six weeks prior to the unprecedented rainfall event on August 25, 2013, two other storms had occurred in the Kyle Canyon drainage area. In addition, the Carpenter 1 fire had denuded much of the area upstream of Inlet Structure No. 3. The fire was less than 50% contained when rain fell on July 12 over the burned area, which caused soot, ash, and other debris to flow over Inlet Structure No. 3 into the Kyle Canyon Detention Basin. Then, on August 18, another storm resulted in more runoff entering the basin containing parts of trees, soot, and ash. After this second event, a 5 feet deep pool of water and debris had accumulated at the outlet structure which was nearly in line with Inlet Structure No. 3.

The Carpenter 1 fire upstream of the watershed and the two subsequent storms had left soil in the drainage area moist and without much vegetation remaining. Both of these factors led to increased runoff when extreme rainfall hit the area upstream of the Kyle Canyon Detention Basin on August 25, 2013.

A radar map of rainfall intensity indicated the eye of the storm, three miles upstream of Inlet Structure No. 3 produced more than eight inches of rain in about four hours. The nearest rain gauge showed 4.10 inches of rain in this time period, which correlated well with the radar imagery. Thus, this isolated storm produced a maximum of nearly twice the annual average rainfall in Las Vegas in less than six hours.

Runoff from the rain produced an estimated maximum flow over Inlet Structure No. 3 of more than 8,000 cfs (40 cfs/foot) and filled the Kyle Canyon basin to a maximum depth of 30 feet. Based on visual observation, the duration of the overflow was less than six hours. See Figure 16 for the stepped RCC inlet prior to and Figure 17 during the overtopping.

Figure 16. Kyle Canyon – Inlet Structure No. 3

Figure 17. Inlet Structure No. 3, Overtopping

Oddly enough, the two other smaller inlets located to the south of Inlet Structure No. 3 did not flow during this event. After the water had been routed through the 300 cfs capacity outlet structure, a large volume of soot, soil, rocks, and other debris was deposited in the basin up to 10 feet deep in places. In order to restore Kyle Canyon Detention Basin to its original capacity, more than 220,000 cubic yards (loose volume) of debris were hauled away to a landfill.

The runoff overtopping Inlet Structure No. 3 was well in excess of the design flow of 2.43 inches and overtopped the left training wall causing erosion of the soil behind it as shown in Figure 19. An inspection of the stepped RCC on the inlet structure showed some surface erosion due to the flow as shown in Figure 18. Thus, the RCC performed well when subjected to a flow well in excess of its design hydraulic capacity that contained large amounts of abrasive flow including rocks.

Figure 18. Steps on Kyle Canyon Inlet No. 3 After Overtopping

Figure 19. Erosion Behind Training Wall Inlet No. 3

The detention basin operated as designed by protecting the housing development immediately downstream of the outlet structure. The CCRFCD felt there would have been extensive property damage and possibly loss of life if the detention basin had not been in place at the time of this localized high intensity rainfall event.

4. CONCLUSIONS

RCC overtopping protection has become the most widely used method for increasing safety of embankment dams by providing increased spillway capacity at low cost.

RCC overtopping protection spillways that have operated have performed very well and as designed. No failure at an RCC protected embankment when overtopped has been reported.

During flooding in Georgia in 2009, four dams overtopped. In this case, various spillway crests as well as exposed and grass covered RCC overtopping protection were tested. In all cases, the dams performed well with very little maintenance.

In Colorado, two RCC protected dams overtopped during floods in 2013. Both stepped RCC surfaces had been exposed to at least 12 years of freeze-thaw cycles which caused some aggregate to be loosened on the surface of the RCC steps. The aggregate in the overflow water caused increased abrasion of the RCC surfaces, especially in the low portions of the spillway.

During an unprecedented storm event near Las Vegas, Nevada, in August 2013, an RCC armored inlet structure to a detention basin was subjected to severe erosional forces. The total volume of debris laden water was so great that more than 200,000 cubic yards (loose volume) of debris in the water was carried over the structure in less than six hours. Erosion of the RCC was minor and the earth embankment easily survived overtopping of the spillway training walls.

5. ACKNOWLEDGEMENTS

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