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Roller-compacted Concrete for Dam Safety Modifications

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Resumo

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Abstract

Roller-compacted concrete (RCC) is used throughout the world for new dam construction. In the United States, RCC is also used extensively for modifying dams with safety deficiencies including stability buttresses for concrete dams, overtopping protection for both concrete and embankment dams, and for constructing spillways. Rapidly placing RCC has an advantage for dam modifications which may only have a limited time to complete construction before placing the structures back in service. The Bureau of Reclamation has used RCC for several unique dam safety modifications. The Portland Cement Association (PCA) has been leading the design and construction industry by promoting the use of RCC in embankment dam overtopping protection since 1985. This paper will discuss the use of RCC for dam modifications including design and construction considerations for RCC construction and case histories of RCC dam safety modifications.*Keywords: RCC, Dam Safety Modification, Concrete Dam, Spillways, Overtopping Protection*

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1 RCC for Dam Safety Improvements - Introduction

Roller compacted concrete (RCC) is an accepted method of constructing new and rehabilitating old dams. The range of applications for dam rehabilitation is tremendous; foundation stability berms, concrete dam stability buttresses, spillways and plunge pools, and concrete and embankment dam overtopping protection. With the variety of rehabilitation schemes comes a wide range of design and construction methodology. Dam safety modifications must be conducted rapidly to minimize disruption of reservoir operations and exposure to dam failure during construction. Construction considerations may differ somewhat for rehabilitation of dams due to the presence of an upstream reservoir and its affect on seepage and downstream dewatering, plant layout, operations requirements, and construction scheduling. RCC can be placed in a short time frame, allowing the dam to resume normal operations quickly.

The key to dam safety rehabilitation is to construct the project as quickly as possible and to have a design that is complimented by a well executed construction program. In most instances, the faster the rate of production, the better the overall RCC performance. Interruptions in RCC delivery, placing, or compaction often have unanticipated ripple effects throughout the job and drastically reduce RCC production. The experiences of the Bureau of Reclamation (Reclamation) for dam and spillway improvements and the Portland Cement Association (PCA) for RCC overtopping protection are discussed. A detailed discussion on applications of RCC for dam safety improvements is the U.S. Society on Dams publication “RCC Construction for Dam Rehabilitation” (USSD, 2003) and Reclamation’s “Roller Compacted Concrete - Design and Construction Considerations for Hydraulic Structures,” (Reclamation, 2005).

2 RCC Mixtures for Reclamation Dam Safety Modifications

RCC mixtures should be designed to provide maximum workability for placing, meet strength and durability criteria, and minimize volume change. For Reclamation dam safety modifications, concrete quality aggregates and gradings are used in conventional concrete and RCC. This also simplifies the number of aggregate stockpiles when there is limited site access. RCC mixtures with clean, well graded sand reduce the mixture water requirement and decrease shrinkage. For dam stability buttresses, design strength requirements can be specified at 180 days or 1 year’s age. These mixtures use up to 50 to 60 percent pozzolan, which decreases thermal temperature rise. Spillways that may operate immediately may have strength requirements at 28 or 90 days age and use less or no pozzolan. Many Reclamation structures are exposed to severe durability environments. Reclamation pioneered the way for using entrained air in RCC for freeze-thaw durability. Typical RCC mixtures for dam safety modifications are shown in Table 1.

3 RCC for Dam Stability Improvements

RCC can be used to correct for dam and foundation static or seismic instability, hydrologic overtopping protection, and to correct deficiencies from concrete deterioration. Often dam stability improvements encompass more than one need.

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Table 1 - RCC Mix Information for Bureau of Reclamation Dam Safety Modifications

Project Name and Location/Year Completed	Cement		Fly Ash		Water	MSA	Compressive Strength	
	Type	Kg/m^3	Class	Kg/m^3	Kg/m^3	mm	MPa	at age
Santa Cruz Dam/ 1990 *	II	78	F	78	101	50	21	1 y
Camp Dyer Dam/ 1992 *	II	82	F	81	90	38	21	1 y
Pueblo Dam and Spillway/ 1998 *	II	71	F	107	84	50	24	1 y
Cold Springs Dam Spillway/ 1996	II	172		0	90	38	50	28 d
Ochoco Dam Spillway/ 1996	II	257		0	129	38	43	28 d
Many Farms Dam Spillway/ 2000*	II	84	F	166	92	19	48	90 d

* Air-entrained RCC

3.1 Design Considerations

The design of a RCC dam stability buttress must first and foremost consider dam safely and reservoir operations during the construction. This usually begins with designing either temporary or permanent outlets through the dam. Next, foundation excavation and treatment should use current practices and keep pace with the rapid advance in RCC construction to avoid cleanup delays. Upstream reservoir storage, downstream releases, and dam foundation permeabilities will influence the capacity and duration of dewatering systems. This can include a central dewatering well at the low point in the excavated foundation or multiple well points.

Seepage at the interface between the existing dam and a new buttress is addressed by providing drains to relieve any hydrostatic pressures that could develop between the two structures. Drains can also tie into an embedded manifold pipe or gallery system. The gallery system provides the advantage of accessibility for cleaning drains and monitoring seepage from specific locations in the gallery. It is often useful to understand the source of seepage and whether seepage is originating in lift lines, internal formed drains, foundation drains, or joints or cracks in the dam.

Bond between the two structures may be an important consideration in a buttress-type modification if the structures will need to act in unison when loads are applied. An evaluation of the temperature load differences between the two structures may be needed to consider the temperature induced expansion and contraction and subsequent loadings that this may create. Contact surfaces should be treated as a construction joint in most cases. Methods of concrete surface preparation include sandblasting, moderate-pressure water blasting, hydro-brooming (high pressure), and hydro-demolition (extremely high pressure). A zone of either conventional concrete or “bonding mortar” is often placed at the dam/buttress contact just prior to RCC. Multiple-arch buttress dams projecting into the RCC stability buttress may not require bond between the existing concrete and RCC. The original buttress elements of Pueblo Dam used a thick sponge-rubber bond breaker to purposely prevent bond between the two structures and allow for some differential movement. The spillway design often will include some means of overtopping protection and energy dissipation measures. This may require reconfiguring the spillway crest, service spillway, adding means of aerating the spillway flow and dissipating energy, and protecting the foundation under overtopping conditions.

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3.2 Example Projects

Three Reclamation dam stability improvements demonstrate the versatility of RCC construction. This includes stability buttresses for arch and concrete gravity dams and foundation stability buttress for the Pueblo Dam spillway.

3.2.1 Santa Cruz Dam

Santa Cruz Dam is a cyclopean concrete arch dam located about 40 km north of Santa Fe, New Mexico on the Santa Cruz River. The dam was completed in 1929, is 46 m high and with a crest length of 152 m, and was rehabilitated in 1989 for the New Mexico Interstate Stream Commission. The dam had safety concerns related to the maximum credible earthquake (MCE) and probable maximum flood (PMF) and the dam was also experiencing severe freezing and thawing deterioration (Metcalf, et al, 1992).

Figure 1 - RCC butress with stepped facing for Santa Cruz Dam (Bureau of Reclamation, 1990).

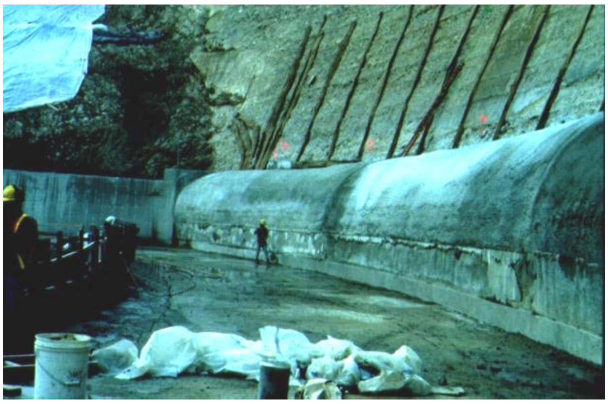

Figure 2 – Shotcrete gallery and buttress contact drains for Santa Cruz Dam (Bureau of Reclamation, 1990).

The requirements for compressive strength were based on the MCE loading condition. The design requirements for the RCC were a compressive strength of 21 MPa at 1 year, cohesion between new and old concrete of 345 KPa at 1 year, and freeze-thaw durability to withstand no less than 500 cycles. Santa Cruz Dam modification was the first to use an air-entraining admixture to improve the freeze-thaw durability of the RCC. RCC was mixed in a continuous weigh batching "pugmill" and was delivered to the placement location by a 115 m conveyor. Conventional concrete was used for the exposed downstream face and at the RCC/foundation rock contact. During construction, the lift placement rate was an average of four lifts per day. A total of 29,260 m^3 of RCC was placed. The unique gallery construction for the dam was accomplished by a shotcrete overlay on a inflatable "Air-o-Form." This forming system worked very well in this application because of the uneven and curved surface of the downstream face of the existing dam (Vaskov, 1990).

3.2.2 Camp Dyer Diversion Dam

Camp Dyer Diversion Dam is located on the Agua Fria River, approximately 56 km northwest of Phoenix, Arizona, and about 1 km downstream from New Waddell Dam. The dam was completed in 1926 as a masonry and concrete gravity structure, has a 187 m crest length a maximum structural height of 23 m, and is owned by the Maricopa Water

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District. Stability analyses of the maximum section of the existing gravity dam indicated that a stability buttress was needed to increase the dead load and sliding resistance of the modified structure. A buttress width of 6 m was selected to accommodate two lanes of construction traffic on the RCC. The 0.8:1 horizontal to vertical (H:V) downstream face of the overflow crest and RCC buttress was stepped for optimum energy dissipation of the maximum 0.6 m deep overtopping flow.

Figure 3 – All RCC stepped spillway at Camp Dyer Diversion Dam spillway after completion (Bureau of Reclamation, 1992).

Figure 4 - Vibrating plate compaction of “toe block” at Pueblo Dam Modification (Bureau of Reclamation, 1998).

The RCC was mixed in a conventional 6 m^3 batch plant with a rated capacity of 115 m^3/hr, and liquid nitrogen injection was used for cooling RCC to meet placing temperature requirements. RCC was delivered by end dump trucks to a hopper that fed a conveyor belt and radial stacker up to the placement. A total of 11,700 m^3 of RCC was required for the dam. This was the first Reclamation dam to utilize exposed RCC at a formed face and is believed to be the first application of flat drains for internal drainage of a concrete dam. The dam was overtopped within 6 months of completion (Hepler, 1990, 1992).

3.2.3 Pueblo Dam

Pueblo Dam is located on the Arkansas River 10 km west of Pueblo, Colorado, and serves as the terminal storage feature for the Fryingpan-Arkansas Project. Construction was started in 1970 and completed in 1975. The dam is a composite, massive slab and buttress concrete dam with earthfill wing dams approximately 3,120 m long. The dam has a structural height of about 75 m. Potential dam safety deficiencies were identified in 1997 and modifications were constructed in 1998 to reduce the potential for sliding failure through the foundation in the excavated spillway plunge pool. The modifications included filling in the stilling basin with an RCC "plug" to the downstream sill and constructing a 14 m thick (horizontal dimension) RCC "toe block" against the upstream stilling basin apron. RCC placed in the plunge pool would provide passive resistance against potential for sliding of the foundation. The plug and toe block also included a reinforced concrete overlay and rock bolts into the foundation. Impact blocks were constructed at the top of the plug to improve stilling basin hydraulics. Since the large RCC placement would crack as it contracted during cooling, longitudinal and transverse contraction joints were induced

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with steel sheets and grouted about 1 year after construction. This is believed to be one of the first designed contraction joint grouting schemes for an RCC dam (Reclamation, 2001).

Because of concern related to RCC lift line bond strength, testing was done after construction for evaluating lift line integrity. It is believed that the 1 day old lift line surfaces may have been damaged by heavy construction traffic during placement of the subsequent lift. Shear and sliding friction tests of cores showed that the lift lines and the zones beneath the lift lines provide acceptable strength (Reclamation, 2001, 2002).

4 RCC Spillways

4.1 Introduction

RCC spillway construction differs somewhat from new dams or dam stability modifications. Except for the spillway basin floor or apron, the volume of RCC per lift is much less than for mass RCC dams. The focus of this discussion will be on open channel type spillways having relatively long lined channels and/or stilling basins. RCC spillways are normally configured as a series of one-lane wide steps placed parallel to and up the slope of an embankment or as a trapezoidal channel with, stepped side walls, or both. Most spillways have upstream control structures such as a weir, ogee crest, or even some kind of regulating gates.

4.2 Design Considerations

One of the primary design considerations for open channel RCC spillways is determining the flow conditions and facing requirements. Most RCC spillways utilize the mass of concrete to resist uplift and incorporate “sacrificial” concrete facing to offset possible erosion or durability concerns. The “stair-step” configuration favors using un-formed RCC with little conventional concrete. However, this does not necessarily mean constructing an uncompacted RCC facing. Edge compaction provides a better flow surface, improves durability, and reduces the volume of waste concrete from spillage.

Design loads such as uplift and duration of operation may influence the overall RCC thickness and whether bond is required between lifts. Bond is normally required between successive lifts and drains with sufficient redundancy are also provided to relieve uplift pressures. Reclamation structures are subjected to a variety of severe durability environments in the western states which influences the quality of materials and mixtures.

The location and placement of drains is an important design issue. Since it is usually not practical to install contraction joints with waterstops in RCC, open contraction joints or cracks in the RCC may allow seepage to enter the foundation during flow conditions. Seepage flow through the joints or cracks or groundwater seepage must be properly filtered and drained. Stagnation pressures at open joints or cracks (Johnson, 1976) can also result in spillway failure due to foundation erosion or hydraulic jacking (Trojanowski, 2004). Drainage combined with thicker, more massive RCC placements can counteract potential uplift pressures. Drains should be carefully located so they will not be crushed by equipment.

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Design and construction of RCC spillways are interrelated. The width of placing lanes has ranged from 2.4 to 3 m on side slopes, depending on bonding requirements, safety, economy, and constructability. Instead of sharp, abrupt turns, the lanes should be widened slightly for safety and rounded or made by a series of chords. The range of side slopes has varied from a steep 0.8H:1V (horizontal to vertical) to a flatter 1.5H:1V, which is more desirable from a safety standpoint.

4.3 Example RCC Spillway Projects

A variety of methods have been used to mix, transport, place, and compact RCC in various spillway configurations. However, careful selection of construction methods and equipment are necessary to avoid "choke points" which interrupt construction productivity in tight working spaces. The task for both designers and contractors is to design the spillway and select equipment and methods that will allow placing "in harmony," avoiding these costly choke points. The following case histories demonstrate the wide variety of design and construction methods and equipment used to construct RCC spillways.

4.3.1 Cold Springs Dam Spillway

Cold Springs Dam is an earth and gravel zoned embankment located near Hermiston, Oregon. The dam was constructed between 1906 and 1908, has a structural height of 30 m and a crest length of 1,050 m. The original dam configuration included a side-channel spillway located on the right abutment. It had a 150 mm thick, lightly reinforced concrete liner founded mostly on soil. The original spillway was found to have two potential failure modes: excessive uplift pressures beneath the original 150 mm thick chute slab and inadequate spillway capacity. A spillway discharge of approximately 9 m^3/s could result in an uplift failure and the original spillway lacked sufficient capacity to pass the PMF, resulting in dam overtopping (Reclamation 1988, 1993).

A modification design was completed in 1994 and construction was completed in 1996. The spillway modifications included an almost complete replacement of the original structure with a wider, more stable RCC structure (Reclamation, 1994). The design discharge for the new side-channel spillway was 800 m^3/s. High velocities (up to 14 m/s) and the potential for high uplift pressures made the massive RCC construction more desirable (Reclamation, 1996). The 0.9 m thick RCC invert slab provides mass for increased stability. The 1.5H:1V side slopes, and 3 m wide lifts were configured to accommodate construction equipment, resulting in an RCC thickness of approximately 1.5 m normal to the slope. An underdrain system beneath the crest, side channel, and discharge chute increases stability by relieving uplift pressures and reducing the potential for piping of foundation materials. The underdrain system consists of transverse perforated collector drains beneath the crest, and longitudinal perforated drains beneath the side channel and chute slabs. The 150 mm HDPE transverse drains are spaced about 30 m along the centerline of the chute to reduce the cross sectional area of the 0.9 m thick RCC invert slab sufficiently to induce cracking. Since the spillway was a side channel design, the upstream end was closed by wrap-around RCC. The original design was a

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typical rectangular section with sharp, angular corners. The specifications allowed for a radius to be formed in the corners.

Figure 5 – RCC side channel spillway at Cold Springs Dam Spillway Modification (Bureau of Reclamation, 1996).

Figure 6 - Vibrating plate compactor for RCC edge at Cold Springs Dam Spillway Modification. (Bureau of Reclamation, 1996).

The mix was designed to provide a compressive strength of 28 MPa at 28 days for immediate operational use, freeze-thaw durability, and erosion resistance. The 13,700 m^3 of RCC was placed in nearly horizontal layers of approximately 300 mm thickness having a maximum sloping grade of 2.5 percent. The RCC was batched in a continuous weigh-batch plant, mixed in a “pugmill”, and discharged to a holding hopper prior to loading in end dump trucks. RCC was hauled to the site in the dump trucks, where it was deposited in a moveable holding bin. A backhoe picked up the RCC and deposited it in front of a dozer. It was spread in uniform layers by the dozer and compacted by the roller. The 3 m wide, 1½H:1V chute side slopes were unformed. However, the dozer blade was retrofitted with side extensions that were in front of and normal to the face of the blade and a tamping plate to vibrate the RCC during the spreading process. As material was spread in front of and below the bottom of the blade, the plate confined and compacted the material along the exposed edge of the chute. These sloping faces were fairly well compacted, achieving about 95 percent of the maximum achievable wet density.

4.3.2 Ochoco Dam Spillway Stilling Basin

Ochoco Dam is located in central Oregon, 8 km upstream of the city of Prineville, which has a population of approximately 5,000 people. The dam was originally constructed around 1920 and has undergone several modifications since then. The spillway was modified in 1996 to address dam safety deficiencies, one of which was the lack of an energy-dissipating structure (stilling basin or plunge pool). Subsurface field explorations near the downstream area of the dam revealed an artesian aquifer with approximately 20 m of head beneath a confining clay layer. Large releases from the spillway without an energy-dissipating structure would cause erosion of the overlying confining layer and exposure of the aquifer and would initiate piping of foundation material from the dam, resulting in dam failure. An RCC stilling basin was constructed in 1996. The stilling basin is a three-staged plunge pool type structure, which changes the flow direction approximately 45 degrees toward Ochoco Creek (Stanton, 1997).

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Several challenges existed at the site including non-uniform foundation conditions on rock and compacted soil, a steep hillside resulting in a 0.8H:1V left side slope and 1.5H:1V on the right side, and an underlying artesian aquifer limiting the depth of excavation and resulting tailwater depth. Drains were placed under the structure to relieve uplift pressure caused by potentially high dynamic flow conditions and to pick up seepage through any future cracking of the RCC. About 14,400 m^3 of RCC were placed over a 3 week period on a 24-hour basis (Reclamation, 1996).

Figure 7 – Ochoco Dam Spillway Modification stilling basin plunge pool spilling during flood of record (Bureau of Reclamation, 1997).

Figure 8. Many Farms Dam Spillway Modification (Bureau of Reclamation, 2000).

4.3.3 Many Farms Dam Spillway

Many Farms Dam is located on the Navajo Indian Reservation in northeast Arizona, approximately 1.6 km east of the town of Many Farms. The reservoir is owned and operated by the Navajo Indian Tribe for irrigation and recreation. The dam embankment, outlet works, and spillway all underwent major dam safety modifications from 1999 to 2001. The original spillway was inadequately sized to pass the PMF and more frequent flood events. Overtopping of the dam embankment would have occurred for flood events greater than 36 percent of the PMF. A new spillway was constructed in 2000 and was designed to pass the PMF having a peak inflow of 3000 m^3/s. The RCC spillway was designed to act as a gravity overlay and was not intended to carry normal structural loads.

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The spillway would experience flow velocities up to 12 m/s during the PMF (Reclamation, 2001). The RCC forming the downstream stilling basin and apron is installed on filter material, which ties into the dike toe drain. A geotextile was provided beneath this RCC to prevent mixing of the filter zone and RCC as it was spread and compacted. The spillway apron and side slopes also had 300 mm wide flat drains to supplement the filter material and toe drain to reduce uplift pressures beneath the stilling basin slab.

The contractor was allowed to compact the exposed RCC face to any slope between vertical and 1H:1V. Saw cuts were used to control cracking along the spillway centerline. The design strength of the RCC was to 28 MPa at 90 days to increase the durability of the RCC. The contractor erected a concrete batch plant immediately downstream of the spillway apron capable of batching and mixing both conventional and RCC. Conventional concrete was used at foundation contacts and bonding mortar was applied on lifts that are one day old or older prior to spreading subsequent lifts. RCC was batched directly into end dump truck and transported and off loaded into a holding bin feeding a telescoping conveyor. A combination of four vibratory passes followed by two static passes was used to obtain the required compaction for the majority of RCC placements. The contractor utilized an excavator with a shop-fabricated vibrating plate to accomplish the edge compaction. The vibrating plate was constructed with a 45-degree angle, which allowed for compaction of the outside 300 mm of the top surface of the lift and the outside sloping face (Reclamation, 2001).

5 RCC for Overtopping Protection of Embankment Dams

5.1 Background Information

The United States Army Corps of Engineers (USACE) implemented the National Dam Safety Inventory and Inspection Program in late 1970s. This program identified lack of adequate spillway capacity being one of the most common deficiencies of hydraulic structures. The required spillway capacity for many dams was found to be much higher than the existing spillway capacity due to present design criteria and in many cases due to changes in spillway classifications because of downstream development. Earthen embankments which were originally built to protect rural pasture and farmland are now protecting residential and commercial developments. Due to their lack of spillway capacity, these dams have been re-classified as hazardous dams and required upgrades to prevent catastrophic failures during maximum design flood events.

RCC has become a popular method to increase spillway capacity and to provide overtopping protection for earthen dams in United States. Since the mid-1980s, RCC has been successfully used on more than 100 earthen dams to armor the downstream slopes and the crests of dams, thereby allowing overtopping of the dams without the risk of failures due to erosion of embankment materials. There are several reasons for the popularity of RCC with designers and owners including simplicity, speed of construction, strength and durability, and economic advantages over alternative methods.

5.2 Design Considerations

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Although RCC spillways and overtopping protection projects can serve as principal spillways for intermittent low flows, most RCC overtopping protection structures are emergency spillways designed to operate at a frequency not exceeding the 100-year storm (Abdo et al., 2007). The Portland Cement Association published a "Design Manual for RCC Spillways and Overtopping Protection," covering latest design and construction methods used in United States (PCA, 2002). Excerpts in this paper are based on information presented in the PCA Design Manual.

Before designing modifications to an existing embankment, an evaluation should be performed to assess the condition of the embankment, foundation, and downstream area, and to determine that the embankment condition is suitable for the intended modifications. Designers should consider the condition of the dam and downstream area, operation frequency of the spillway, required spillway capacity and flow characteristics in order to properly locate and size the spillway. The evaluation should also include a prediction of the behavior and condition of the embankment following the construction of the spillway. An evaluation of the potential aggregate sources for RCC is another important part of the design. On-site natural deposits, existing nearby quarries, and potential new quarries should be considered. Investigations are conducted to identify properties of aggregates and to incorporate these properties in the project specifications. With the increasing cost of fuel and transportation, the location of the aggregate source and its proximity from the job site has become one of the most important factors affecting the cost of the RCC materials. For remote sites where large volumes of RCC are needed, all possible on-site and nearby potential mining sources should be considered. Once potential sources are identified, aggregate samples should be obtained and tested to determine the properties of the most readily available and cost effective materials that are suitable for use in RCC.

A typical RCC spillway section for overtopping protection of an embankment dam as shown in figure 7 includes a filter/drainage system, an upstream approach apron, spillway chute, downstream apron or stilling basin, training walls, and upstream and downstream cutoff walls. A filter/drainage system is typically installed under the RCC to prevent transport of embankment materials through RCC joints or cracks and to drain seepage water and prevent excessive uplift pressures on the RCC. The approach apron located upstream of the spillway crest control section functions to reduce erosion and reduce seepage from the reservoir under the spillway chute. For many overtopping protection spillways, the approach apron also serves as a broad-crested weir, which simplifies construction but has a relatively low-hydraulic efficiency. Sharp-crested and Ogee-crest weirs having higher hydraulic efficiencies have also been used. Optimizing the design and reducing the overall cost of the project requires evaluating the different weir configurations and resulting size of spillway capable of passing the design flow.

Most RCC spillway chutes are stepped to increase energy dissipation and thereby reduce the required size of downstream apron or stilling basin. The chutes are typically built using the stair-step method of construction using horizontal lifts 30 cm thick by 2.4 to 3.0 m wide. The width of the RCC lift should be as required to insure sufficient mass to resist uplift forces. However, it has been found that this width for many projects may be less than the

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width required to accommodate construction equipment such as haul trucks, dozers, and vibratory rollers. The edges of lifts or steps can be formed or unformed depending on the desired energy dissipation and aesthetics. For unformed edges, the width of each lift should be overbuilt by approximately 30 cm to allow for erosion of the uncompacted edge materials. Formed steps on projects built in United States varied in height from 30 to 90 cm using 1, 2, or 3 lifts for each step.

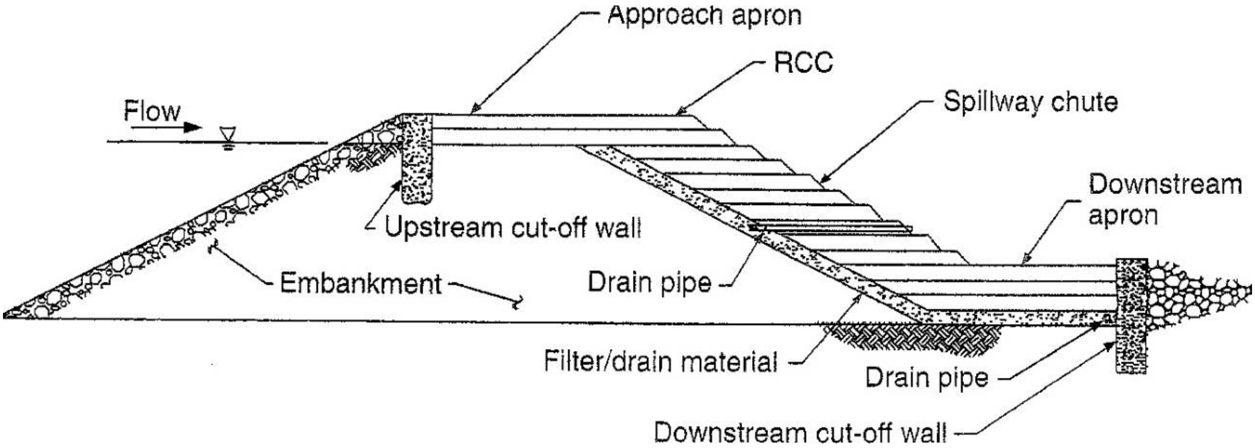

Figure 7 – Typical Section of RCC Overtopping Protection (PCA design manual, pp. 30)

Cutoff walls are typically located at the upstream and downstream ends of the RCC spillway. The function of the upstream cutoff wall is to decrease seepage under the spillway and to reduce scour potential. The primary function of the downstream cutoff wall is to prevent undermining of the spillway from channel erosion. Cutoff walls can be built using RCC, conventional concrete, or sheet piles. For more detailed information on the design of RCC spillways, readers are encouraged to refer to the PCA Design Manual and the references listed therein.

5.3 Typical RCC Mixtures for Overtopping Protection Projects

Table 2 lists RCC mix information for a few projects. Type I or Type I/II Portland cement have been used on most projects. Class F or C fly ash have also been used on projects large enough to justify the cost of setting up an additional fly ash silo at the mixing plant. Aggregates for RCC mixtures used on early projects built in the 1980s generally consisted of well-graded aggregates with a large maximum size to reduce voids and required mortar content. Considering the increased difficulty of controlling segregation with a large maximum size, combined with the narrow placement area for RCC overtopping protection, a 37.5 mm or smaller maximum size is now preferred and commonly selected for RCC overtopping structures.

5.4 Example Projects

To date, approximately 100 RCC overtopping protection projects have been completed in United States. One example is Yellow Creek Watershed No. 14 (Y-14) located in Gwinnett County, Georgia. The dam was constructed to protect pasture and farm land

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and now provides flood protection for subdivisions, apartment complexes, office parks, retail businesses, bridges, and roadways. The original height of the dam was 12.2 m. The structure was constructed with a two-stage principal spillway riser and pipe outlet and a 15.2 m wide earthen auxiliary spillway located east of the dam site.

Table 2 - RCC Mix Information for Example Overtopping Protection Projects

Project Name and Location/Year Completed	Cement		Fly Ash		Water	MSA	Compr. Strength	
	Type	Kg/m^3	Class	Kg/m^3	Kg/m^3	mm	MPa	at age
Lower Lake Royer Dam, Maryland/1995	I	119	---	60	122	37.5	---	---
Lake Tholocco Dam, Alabama/2000	II	163	F	30	---	37.5	---	---
Red Rock Detention Basin, Nevada/2001	---	216	---	44	---	---	---	---
McKinney Lake Dam, North Carolina/2001	I/II	267	NA	0	167	37.5	20.7	28 days
Yellow River Watershed No. 14, Georgia/2003	I	148	C	148	150	37.5	20.7	28 days
Yellow River Watershed No. 17, Georgia/2005	I/II	148	F	48	147	37.5	15.5	28 days

Note: --- denotes data not available

When the structure was found not in compliance with applicable dam safety regulations, analyses identified that the most cost effective solution was construction of an RCC spillway overtopping the existing dam and abandoning the existing earthen auxiliary spillway. Due to site constraints, Golder Associates, Inc. (Golder) designed an arc shaped chute spillway with an ogee weir to minimize convergence impacts and provide favorable hydraulic performance. The RCC spillway steps were constructed by forming the front edge of the 30-cm high, 3-m wide steps as shown in figures 8 to 11.

The chute steps were constructed with a 3H:1V slope and the training wall steps were constructed with a 2H:1V slope. Bedding mix was required on the first four lifts, last two lifts, and on every cold joint having a joint maturity greater than 2000 degree F-hours. The new RCC spillway safely routes the full Probable Maximum Precipitation (PMP) storm through the watershed, with a peak discharge capacity of about 450 m^3/sec and maintains the peak storm stage below the original dam crest elevation (PCA Publication PL461, 2005).

Another example is Lake Tholocco Dam located in south Alabama and owned by the US Army Corps of Engineers (USACE). Constructed in the 1930s, this dam is an earth embankment creating a 275-hectare lake for training of military personnel and for recreational activities. The dam has 15.2 m reinforced concrete service spillway with a fixed ogee crest. The original construction included an earthen emergency spillway, which operated regularly causing severe erosion. During July 1-4, 1994, tropical Storm Alberto failed the earthen spillway and the reservoir remained empty for six years. In 2000, the USACE elected to re-build the failed dam and install an RCC auxiliary spillway with a collection channel in the embankment adjacent to the reinforced concrete service spillway shown in Figure 12. The design called for a 472 m-long by 11m-high stepped spillway

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constructed with 30 cm thick RCC steps. The crest elevation was set to discharge water from rainfall events once every one to two years, and the design maximum overflow depth was 2.0 m. The RCC lifts varied in width from 2.4 to 3.7 m. The spillway chute was designed at 6H:1V and the downstream side of the collection channel was 3H:1V. The spillway has been overtopped a few times as shown in Figure 13 with a maximum overflow depth of 0.9 m. On-site personnel report that the spillway has been performing well with no signs of distress..

Figure 8 - Foundation preparation and construction of conventional concrete downstream cutoff wall at Y-14 (Golder 2003)

Figure 9 - Equipment used to haul, place, spread and compact the RCC (Golder 2003).

Figure 10 - Construction filter/drainage layer and first few lifts of RCC with formed edges (Golder 2003).

Figure 11 - Completed RCC Spillway with reinforced conventional concrete Ogee Crest (Golder 2003).

5.5 Field Performance of RCC Spillways and Overtopping Protection

Because RCC emergency spillway and overtopping protection projects are designed to operate infrequently during major flood events, limited information is available on the actual performance of these types of structures. However, the few that have operated performed satisfactorily with no evidence of excessive wear or structural distress. Several research projects have confirmed the excellent abrasion resistance and durability of RCC. Comparative tests on soil-cement, RCC and conventional concrete showed RCC to have a greater abrasion resistance than conventional concrete of higher strength (PCA Publication RD 126, 2002). This was primarily due to the presence of a larger percentage

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of aggregate in the RCC mixture and less paste. Despite the research findings, there is still the need to evaluate the reliability and performance of RCC under actual field conditions.

Figure 12 - RCC spillway and collection channel at Tholocco Lake Dam (USACE, 2000)

Figure 13 - RCC spillway during an overtopping event (USACE, 2005).

The Portland Cement Association reviewed available data from six projects that have experienced repeated overtopping flows and reported the review results in a paper published in 2007 (Abdo et al., 2007). The projects represent applications where high velocities and significant overflow depths, freeze-thaw cycles, and/or very abrasive flows took place. The study revealed that projects built with formed lift edges and compacted to a high density at the exposed edges experience no or very limited wear near the tread corners of the steps. However, projects built without forming the lift edges produced zones of lower density RCC as compared to the density of formed RCC compacted with vibratory rollers. The repeated flows caused limited erosion of the uncompacted materials at the lift edges. The erosion rate typically decreases as the uncompacted material is lost and material compacted to a higher density is exposed. The study concludes that to prevent erosion at the lift edges, the edges should be formed and compacted to a high density and segregation must be limited.

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