Facing Systems for Roller-Compacted Concrete Dams & Spillways

Prepared by Gannett Fleming, Inc.

PORTLAND CEMENT ASSOCIATION

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FACING SYSTEMS FOR ROLLER-COMPACTED CONCRETE DAMS & SPILLWAYS

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Note: This document is written in English units. To convert to metric units use the conversion table presented below.

Selected Conversion Factors to SI Units

To Convert	Into	Multiply by
Square Yard (CY)	Square Meter (m^2)	0.8361
Square Foot (Ft^2)	Square Meter (m^2)	0.0929
Foot (Ft)	Meter (m)	0.3048
Inch (In)	Millimeter (mm)	25.4
Ton (2000 lb)	Kilogram (kg)	907.185
Pound (lb)	Kilogram (kg)	0.45359
Pounds Per Square Inch (psi)	Kilopascals (kPa)	6.8948
Cubic Yard (CY)	Cubic Meter (m^3)	0.7646
Horsepower (HP)	Kilowatt (kW)	0.7457
Fahrenheit (°F)	Celsius (°C)	5/9(°F – 32)
Cubic Foot (CF)	Liter (l)	28.316
Gallon (U.S)	Liter (l)	3.78
Fluid Ounce per Pound (fl.oz.)/lb	Milliliter per Kilogram (ml/Kg)	65.2

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CHAPTER 1

Introduction

1.1 Background

Modern era concrete gravity dams have been constructed with conventional Portland Cement concrete mixes using temporary formwork to contain the plastic concrete until it “set up” and was self supporting. The majority of gravity dams have a vertical upstream face and the familiar sloping downstream face of about 45 degrees (examples: Shasta, Grand Coulee, and Folsom dams). The introduction of roller-compacted concrete (RCC) technology in the late 1970s - early 1980s was the result of intensive research and development carried out by dam designers throughout the 1970s. The primary objective of the new technology was to achieve radical cost reductions in every phase of concrete dam design and construction including materials, mix designs, temperature control, contraction joint grouting, forming, mixing, and placing.

Prior to RCC dams, the upstream and downstream faces of conventional concrete dams were generally not considered as a separate design element, and there were no special costs allocated to the faces of the dam. The faces of the dam were simply the natural outcome of casting fluid concrete against temporary, removable forms. No special provisions were required other than specifying the quality and finish of the surface. The unit cost per cubic yard of concrete for constructing the dam body was inclusive of all costs associated with forming and placing the mass concrete with no special provision for the faces of the dam.

The introduction of RCC construction techniques sought to reduce the cost of the form materials and the high labor costs of setting, stripping, and resetting the forms. This led to innovations for building both the upstream and downstream faces of RCC dams. Special treatments and construction techniques such as “stay-in-place” forms that become an integral part of the dam, and other methods were developed and continue to be refined. The innovations were intended to speed construction and to avoid the sunk costs of the forms and the labor costs of stripping and resetting of forms. As a result, engineers began to consider the dam faces as a separate design element and to break out the portion of costs allocated to building so-called “facing systems”from the single unit cost of the mass concrete.

A variety of upstream and downstream facing systems have been used on RCC dams with varying degrees of success. Early RCC dams experienced significant seepage, either through horizontal lift joints and / or vertical transverse cracks. As a result, more sophisticated upstream facing systems using conventional concrete, precast concrete, geomembranes, or combinations of these systems have been incorporated in recent RCC dams with greater success. Downstream facing systems have also been quite varied, including un-faced RCC, and conventional concrete placed concurrently with RCC or following RCC placement. The exposed surface of the downstream face is most commonly configured to have either a continuous slope or stepped surface. Stepped configurations are often used in the overflow section to provide the added benefit of energy dissipation for spillway flows.

Larger and higher RCC dams than those which have been constructed over the last two decades are scheduled for design and construction in the near future. As the body of RCC experience has increased, the cost, constructibility, and performance of various upstream and downstream facing systems have been closely studied and reported. As a result, some facing systems have gained wide acceptance and use while others have been abandoned. Most facing systems which have performed well and are widely used continue to be improved and refined with each new dam.

Although the type of facing system selected for a new dam is site specific and is based on a number of criteria, all successful facing systems for RCC dams have one feature in common – they do not impede the potential for high RCC placement rates. This should always be a consideration in selecting a facing system for an RCC dam. Selection of the facing system(s) for an RCC dam must also consider the intended purpose of the facility, operation and performance criteria, local climatic conditions, materials availability, dam size, owner preferences, and public perception. General selection criteria should be based on many factors including constructibility, watertightness, durability, appearance, and cost. The general selection criteria will and should differ between the upstream and downstream faces of the dam.

This report presents a comprehensive summary and general evaluation of the upstream and downstream facing systems used on RCC dams and their spillways. Types of facing systems available, the general criteria for selecting a facing system, special site and structure considerations, and state-of-the-art trends in facing system construction for RCC dams are emphasized.

1.2 Facing System Statistics for RCC Dams Worldwide

To date, approximately 214 RCC dams with heights over 50 feet have been constructed worldwide. Of these dams, 37 (17.3 percent) are over 300 feet high. Seventeen different facing systems have been constructed on RCC dams worldwide. Table 1.1 presents statistics for these facing systems based on a published survey prepared by Dr. M. R. Dunstan (Dunstan, 2000).

Some of the upstream facing systems are combinations of facing systems which provide redundant seepage protection. Several of the facing systems used are unique to a particular dam site and are generally not available or possible at most other dam sites. Other facing systems presented in Table 1.1 are unique to a country such as “RCC against precast concrete panels with hot-poured Membrane” which has been used exclusively in China, and “conventional reinforced concrete cast before RCC placement” which has been used predominantly in France.

A close examination of the types of facing systems used in each country shows that the designers in some countries have a strong preference for a particular facing system. For example, all 37 RCC dams constructed in Japan, representing 17.3 percent of

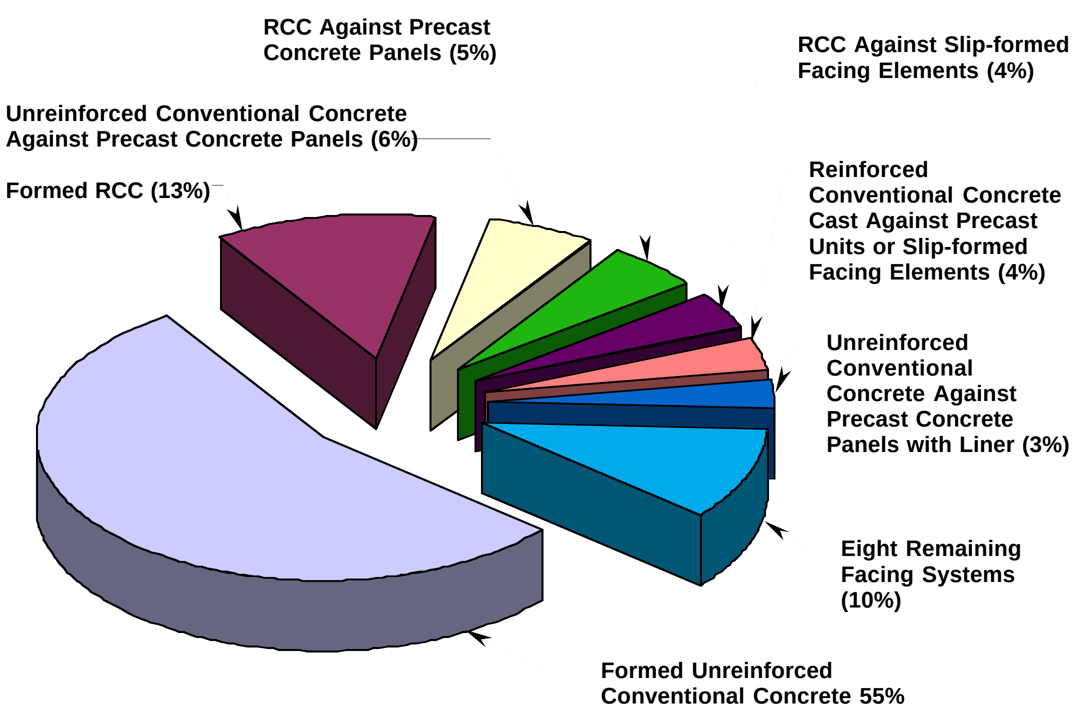


Figure 1.1 Facing systems statistics for RCC dams in the United States.

Table 1.1. Summary of Facing Systems. Used on RCC Dams Worldwide with Heights Greater Than 50 Feet Based on Published Survey of 214 RCC Dams (Dunstan, 2000)

	Description of Facing System System	Upstream Facing System (Percent)	Downstream Facing System	
			Dam (Percent)	Spillway (Percent)
1	Formed Unreinforced Conventional Concrete	54.7 %	50.0%	67.0%
2	Formed RCC	12.6 %	21.2 %	9.6 %
3	Unreinforced Conventional Concrete Against Precast Concrete Panels	6.1 %	3.4 %	0.5 %
4	RCC Against Precast Concrete Panels 0.5 %		5.1 %	1.9 %
5	RCC Against Slip-formed Facing Elements	.2 %	5.3 %	3.0 %
6	Reinforced Conventional Concrete Against Precast Units or Slip-formed Facing Elements	3.7 %	0.5 %	11.2 %
7	Unreinforced Conventional Concrete Against Precast Concrete Panels with Internal Liner	3.3 %	0.5 %	—
8	Unreinforced Conventional Concrete Against Formwork with External Liner	1.9 %	—	—
9	RCC Against Precast Concrete Panels with Hot Poured Membrane	1.9 %	—	—
10	RCC Against Formwork with External Liner	1.4 %	—	—
11	RCC Against Precast Concrete Panels with Liner	1.4 %	—	—
12	Reinforced Conventional Concrete Cast Before RCC Placement	1.4 %	—	—
13	Reinforced Conventional Concrete Cast After RCC Placement	1.4 %	1.0 %	5.6 %
14	RCC Against Precast Concrete Blocks	0.5 %	8.7 %	0.5 %
15	RCC Against Fill	0.5 %	0.5 %	—
16	Mechanically Compacted Unformed Face of RCC	—	1.9 %	—
17	Unformed Face of RCC	—	5.8 %	2.0 %
	Total	**100 %**	**100 %**	**100 %**
	Stepped Face	1.4 %	43.8 %	35.5%

A pie chart showing the distribution of upstream facing systems used on RCC dams worldwide is presented in Figure 1.1.

Table 1.2. Summary of Upstream and Downstream Facing Systems on RCC Dams with Heights 40 Feet in the United States.

Facing System:

1. Formed RCC
2. Earth or Rock Fill Placed Concurrently with RCC
3. Formed Conventional Unreinforced Concrete
4. Formed Reinforced Conventional Concrete Against RCC
5. RCC Against Precast Panels
6. RCC Against Precast Panels with Internal Liner
7. Unformed RCC
8. RCC Against Slipformed Facing Elements
9. RCC Against Precast Concrete Blocks/Elements
10. Formed Conventional Unreinforced Concrete with External Liner
11. Formed RCC with External Liner

■ Vertical or Sloping Face

■ Stepped Face

Purpose:

F Flood Control
R Recreation
W Water Supply
H Hydropower
G Groundwater Recharge
P Pollution Control

RCC Dam	State	Date	Purpose	Height Feet	Length Feet	RCC Volume (CY)	Upstream Facing System 1	2	3	4	5	6	8	10	11	Downstream Facing System – Dam 1	2	3	4	5	7	8	9	Spillway 1	3	4	7	8	9
1. Willow Creek	OR	1982	F,R	169	1,780	433,000					V										V						V		
2. Winchester	KY	1984	W	74	1,192	32,000						V								V	V				V				
3. Middle Fork	CO	1984	F, W	124	410	55,000			V									S								Conduit			
4. Galesville	OR	1985	W, F, R	163	950	210,000								V							V						V		
5. Great Hills	TX	1985	R	41	450	13,000	V														V						V		
6. Grindstone Canyon	NM	1986	W	139	1,416	115,000			V									S							V				
7. Monksville	NJ	1986	W	157	2,200	287,000			V									V							S				
8. Lower Chase	AZ	1987	F	64	400	18,000			V									S							S				
9. Upper Stillwater	UT	1987	W	294	2,673	1,471,000							V									V						S	
10. Elk Creek	OR	1988	F	83	1,197	348,000			V													V				V			
11. Stagecoach	CO	1988	H, W, R	150	380	44,000			V									S							S				
12. SW Freese (Stacy)	TX	1989	W	103	568	117,000				V											V					V			
13. Marmot	OR	1990	H	55	194	7,600			V									S							V				
14. Oxhide Mine #3A	AZ	1990	W	50	278	9,000								V							V								
15. Quail Creek South	UT	1990	W	137	2,000	170,000			V									V			V					Conduit			
16. Freeman	CA	1990	G	55	1,200	132,000		V													V						V		
17. Cuchillo Negro	NM	1991	F	164	610	97,200					V										V						V		
18. Nickajack	TN	1991	H	55	1,316	103,000		V								S								S					
19. Victoria	MI	1991	H	120	301	43,200			V							S								S					
20. Town Wash	NV	1992	F	59	865	56,000			V				V			V								S					
21. Lake Alan Henry	TX	1992	W	82	276	29,400				V											V				V				
22. Christian E. Siegrist	PA	1992	W	130	672	85,000						V							V	V						V			
23. Zintel Canyon	WA	1992	F	127	450	70,200					V										V						V		
24. Elmer Thomas	OK	1993	R	115	425	38,000			V									V								None			
25. Spring Hollow	VA	1993	W	240	970	310,000						V									V					None			
26. Hudson River #11	GA	1993	W	68	550	34,000						V						S							S				
27. Rocky Gulch	AZ	1994	P	58	180	8,050			V												V					None			
28. Reichs Ford	MD	1994	F	45	350	30,000					V										V						V		
29. Peterson Lake	CO	1995	W	63	260	9,300			V									S							S				
30. Big Haynes	GA	1996	W	88	1,400	93,700						V				S					V								S
31. Tie Hack	WY	1997	W	154	585	83,000			V									S							S				
32. Penn Forest	PA	1998	W	180	2,060	370,000						V					V			V						Separate			
33. Buckhorn	NC	1998	W	44	2,500	87,000						V								V	V				S				
34. Bullard Creek	OR	1999	F	52	360	9,160	V											S							S				
35. Barnard Creek	UT	1999	F	59	150	3,400								*	V	S								S					
36. Hughes River	WV	2000	F,W,R	86	1,000	85,500						V											V			V			
37. Pajarito	NM	2000	F	118	200	67,000		V													V						V		
38. Trout Creek	CO	2000	R	101	125	12,000			V									S							S				
39. Hunting Run	VA	2001	W	89	2,400	136,000						V								V	V						V		
40. Olivenhain	CA	2001	W	306	2,580	1,400,000									V			S							S				
						Total	2	3	15	2	4	9	2	2	2	5	1	14	1	5	18	2	1	4	14	4	9	1	1

*** Shotcrete Used as the upstream liner after RCC Placement**

the dams constructed worldwide, were constructed using unreinforced conventional concrete to face both the upstream and downstream faces of the dams. None of these dams were constructed with a stepped downstream face.

1.3 Facing Systems Statistics for RCC Dams In the United States

Of the 214 RCC dams with heights greater than 50 feet constructed worldwide, 32 (15 percent) were constructed in the United States. Three additional RCC dams with heights greater than 50 feet are currently under construction: Hughes River Dam in West Virginia, Hunting Run Dam in Virginia, and Olivenhain Dam in San Diego, California. When completed in the year 2003, Olivenhain Dam will be the tallest RCC dam in North America at 308.5 feet, requiring approximately 1,420,000 cubic yards of RCC.

Of the 17 facing systems used on RCC dams worldwide, 11 have been used on RCC dams in the United States. A summary of the facing systems used on RCC dams in the United States with heights greater than 40 feet is presented in Table 1.2. Of these facing systems, five were first used in the United States including: (1) RCC against precast panels (Willow Creek Dam), (2) RCC against precast panels with an internal liner (Winchester Dam), (3) Slip-formed facing elements (Upper Stillwater Dam), (4) Reinforced conventional concrete cast against RCC (Stacy Dam), and (5) Unformed downstream face (Willow Creek Dam). None of these 11 facing systems are unique to the United States. Middle Fork Dam was the first RCC dam in the world to have a stepped downstream face. Approximately 31 percent of the RCC dams constructed in the United States have a stepped downstream face in the non-overflow section, and approximately 50 percent have a stepped face in the overflow section.

1.4 Recent Developments in RCC Dam Construction and Their Impact on Facing System Selection

1.4.1 General. Although RCC has been used for construction of dams worldwide for nearly 20 years, new techniques, materials, and construction procedures are still being developed. Further, better understanding of RCC behavior is allowing the planning, design, and construction of RCC dams of unprecedented height.

"Conventional" RCC construction in the United States has typically consisted of constructing one-foot thick lifts from one abutment to the other prior to initiating construction of the next lift. This approach results in the greatest lift joint maturity and, therefore, also results in the lowest lift joint strength and highest permeability unless special measures are taken. For dams in low to moderate seismic zones, adequate lift joint shear and tensile strength can usually be achieved with only minimal use of bedding mortar. In warm weather conditions, however, a retarding admixture may be needed to develop adequate bonding of lifts if bedding mortar is not used. Full bedding of lift joints and/or use of a retarding admixture is often required for dams in high seismic zones to maximize lift joint tensile and shear strengths.

In the past several years, variations in RCC placement methods have been developed to dramatically improve lift joint quality and/or minimize the number of lift joints. These include the monolith or staged-monolith method of construction, thick lift placement, and the sloping lift method of placement developed in China. These new construction techniques and procedures can have a significant impact on the selection of the facing system(s) for the dam.

1.4.2 Monolithic or Staged-Monolith Construction of RCC Dams. Several recent RCC dams, including Big Haynes Dam and Penn Forest Dam in the United States, and others worldwide have been constructed either fully or partially in monoliths, similar to the practice traditionally used to construct gravity dams using conventional mass concrete. For monolithic construction, one or more monoliths between transverse contraction joints are constructed; then operations are moved to the next monolith or set of monoliths. The staged monolith

Figure 1.2. Monolithic construction of Big Haynes Dam, GA.

approach raises one or more monoliths several lifts; then adjacent monoliths are advanced. The main advantage of this approach is that lift joint maturity can be dramatically decreased by rapid placement of lifts within the “active” work area. As a result, lift joint tensile and shear strengths are increased, and the use of bedding mortar for cold joints can be decreased. Additionally, the approach allows for construction to begin in one area while excavation, gallery construction, foundation drilling, final foundation cleanup operations, or other work activities are ongoing in another area. The main disadvantage of monolithic or staged-monolith construction is the need for formwork at the end of each monolith. The 88-foot-high Big Haynes Dam in Georgia is an example of an RCC dam constructed using the staged-monolith method (Figure 1.2). The 304-foot high Balambano Dam in Indonesia also used the staged-monolith construction method (Figure 1.3).

Figure 1.3. Monolithic construction of Balambano Dam, Indonesia.

1.4.3 Sloping Lift RCC Construction. Another new RCC construction method that favors increasing the rate of RCC placement while minimizing lift surface exposure is sloping lift RCC construction. For this method of placement, a thick “block” of RCC is advanced by placing a number of individual layers sloping from the top of the block down to the top of the previous block of layers. The slope of the layers is set according to placing capacity, the scale of the placing area, and what is determined to be an acceptable length of time between placement of each individual layer. A steeper slope decreases the length of time between placement of each layer; however, too steep a slope can result in inefficient use of construction equipment. Each individual layer is compacted with vibratory rollers. The goal is to reduce the time between placement of each individual layer, thereby increasing lift joint quality without the use of bedding mortar. Bedding mortar and extensive lift surface cleaning are only required on the surface of each block of RCC.

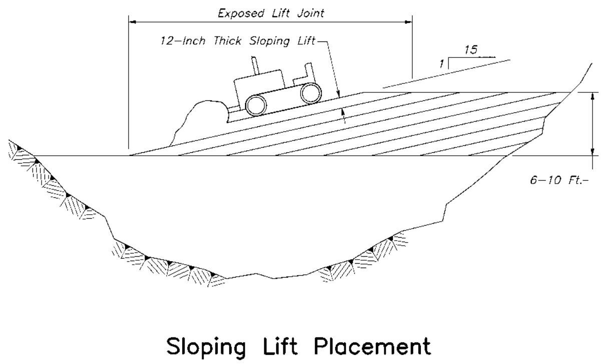


Figure 1.4. Illustration of sloping lift placement (exaggerated scale).

The sloping lift method of construction was first used at the Jiangya Dam project in China in 1997. The method was termed “Horizontally Advancing Sloped Layer Construction.” For this project, the best slope varied from 15H:1V to 20H:1V depending on the elevation in the dam. The slope was established to provide a large enough placing area for efficient use of the construction equipment, while also keeping the area small enough to maintain exposure of the individual layers at 2 to 4 hours. At the Jiangya project, 12-inch individual layers were used, and a total “block” thickness or vertical height of 10 feet was advanced from abutment to abutment (Changquan, 1999).

Although the sloping lift method of RCC placement has several advantages, it also has the disadvantages of a more complicated grade control and the need for treatment of considerably more lift edges as compared to conventional RCC placement in horizontal or near-horizontal lifts. In addition, if sloping lifts are advanced from abutment to abutment (most cases), forming steps on the downstream face is very difficult. On very large dams, if the lifts are advanced in the upstream / downstream direction, a stepped face could be constructed without difficulty.

1.4.4 Thick Lift Placement. Horizontal lifts with a one-foot thickness have more or less become standard worldwide. However, both designers and contractors have investigated the use of horizontal lifts with a thickness up to 24 inches, or double the standard practice. Both monolithic and sloping lift RCC construction are conducive to using thicker horizontal lifts. Construction of thicker horizontal lifts is typically limited by the capacity of the mix plant, delivery system, and spreading equipment. While thick lift placement does not necessarily increase lift joint shear strength, it does decrease the number of lift joints that might require treatment such as cleaning and application of bedding mortar. Thicker lifts can be accomplished either by placement and compaction of a single, thicker layer or by spreading RCC in several advancing horizontal layers to build a thicker final lift similar to the procedure used at Elk Creek Dam, constructed in 1988. At Elk Creek Dam, RCC was spread in 6-inch layers, each individually compacted by dozer action. After four 6-inch layers were placed, the 24-inch thick lift was then compacted with vibratory rollers. Successful consolidation of the thicker lifts at Elk Creek Dam required both a low Vebe time of 8 to 10 seconds, and significant reworking of the RCC by dozers during the spreading operation of each individual 6-inch layer. According to nuclear density test results, compaction was essentially completed by the dozer action alone (Hopman, 1988).

Placement of RCC in lifts thicker than the standard 12 inches was investigated as part of the design phase for Olivenhain Dam. Lift thicknesses of 15, 18, and 24 inches were investigated. Extensive density testing was performed using a lift thickness of 18 inches spread in two 9-inch layers. As with Elk Creek Dam, it was determined that a lower Vebe time was required to obtain adequate consolidation of thicker lifts. For the Olivenhain Dam thick lift trials, a Vebe time of about 14 to 16 seconds was used. In addition to the lower Vebe time, 8 passes with a 20-ton vibratory roller were required to complete the compaction process to an acceptable level. As a comparison, for 12-inch thick lifts placed in a single layer at a Vebe time of 20 to 25 seconds, adequate compaction was achieved with 8 passes of a 10-ton vibratory roller. It was decided that placement of the RCC in thicker lifts was not appropriate for the Olivenhain Dam project in part due to additional exposure of uncompacted material to the hot, dry climate, damage to the upper zone of the lift caused by the heavier roller, and the need for additional mix water to provide the necessary low Vebe times (and thus additional cement to meet the required strength). Although not adopted for the Olivenhain Dam project, thicker lift construction may be a viable alternative for other projects.

1.4.5 Impacts of New RCC Construction Methods On Facing Systems. Monolithic construction, sloping lift construction, and thicker RCC lifts all involve minimizing lift surface exposure by concentrating RCC placement within a more narrow area. This in turn can result in increasing the rate of lift placement or rate of vertical rise of sections of the dam. These construction methods can impact facing systems that are conducive to traditional RCC construction that involves placing one lift at a time across the entire length of the dam. For example, facing systems such as RCC against slip-formed or extruded elements, that require long continuous runs across the dam to be economical, are not compatible with monolithic or sloped lift construction. Increasing the lift thickness can impact the construction of facing systems that require other materials to be placed concurrently with RCC placement, such as unreinforced conventional concrete against formwork or RCC placed against earth/rock fill. Additional temporary bracing of the forms may be required if RCC lifts are placed rapidly, such that the rate of vertical RCC placement does not permit adequate time for the RCC to gain strength. This may affect the cost of facing systems that use stay-in-place forms such as precast concrete panels, where the lower panels provide the lateral support for the upper panels. If vertical placement of RCC is too rapid, the construction limitations for some facing systems may become critical and prohibit their use. As previously noted, construction of the facing system must not impede the potential for high RCC placement rates.

CHAPTER 2

Upstream Facing Systems for RCC Dams

2.1 Criteria for Evaluating Upstream Facing Systems

2.1.1 General. The general criteria for evaluating upstream facing systems for most RCC dams during the design phase includes the following five factors:

1. Appearance
2. Constructibility
3. Seepage Control
4. Durability
5. Cost

The importance or weight that each factor has on the selection of the upstream facing system depends on the intended purpose of the dam, local climatic conditions, materials availability, dam size, and owner preferences. Most RCC dams with a permanent reservoir require that the upstream facing system provide proven, reliable, long-term seepage control, whereas RCC dams intended to impound water for infrequent and short durations for the purpose of flood control may use a less impermeable facing system. A brief discussion of each of the evaluation criteria is presented below. A general assessment of the overall rating of each of the upstream facing systems for each of the evaluation factors is presented at the end of this section.

2.1.2 Appearance. Appearance is normally a standard established to satisfy aesthetic requirements set by owners or local agencies. The appearance of the facing system can be very important where public perception of the condition, stability, and safety of the structure is essential. The appearance of some upstream facing systems such as exposed RCC can evoke unwarranted concern from those who are unfamiliar with this technology. For screening purposes, appearance is categorized as "Good," "Fair," and "Poor."

2.1.3 Constructibility. Constructibility includes an assessment of: (1) the availability of the construction materials and specialized labor and / or equipment required to perform the installation, (2) the impact that the installation / construction of the upstream facing system has on the overall construction schedule, (3) the impact that the construction of the facing system has on the RCC placement operations, and (4) the complexity of the construction techniques needed to construct the facing system. For screening purposes, constructibility is categorized as "Routine," "Moderate," and "Difficult." A primary consideration when evaluating the constructibility of the upstream facing system for RCC dams is the impact it has on the placement of RCC. The selected facing system should not impede or control the rate of RCC placement.

2.1.4 Seepage Control. Key factors related to seepage control include the permeability of the facing system, whether or not the facing system is drained or undrained, and the performance of the facing system should the dam experience minor movements or cracking. A drained upstream facing system can accomplish the removal of water migrating through lift joints in the body of the dam, thus lowering saturation levels and pore pressures in the dam, with beneficial effects on the stability safety factors, on AAR phenomena, and on appearance. A drained upstream facing system also permits more accurate monitoring and control of seepage. For screening purposes, seepage control is categorized as "Good," "Fair," and "Poor."

2.1.5 Durability. Durability can be influenced by a number of site-specific factors including (1) chemical attack, (2) solar radiation, (3) thermal expansion and contraction, (4) wave and ice loading, (5) freeze / thaw cycles, (6) seismic loading, and (7) vandalism. The relative weight of consideration placed on the ice loading and freeze / thaw cycle factors should be climate-dependent. Other durability considerations include maintenance requirements and the anticipated service life of the facing system. Durability also includes an assessment of what would be involved to repair or replace the facing system once its design life is exceeded or should a defect in, or failure of, the facing system occur. For screening purposes, durability is categorized as "Good," "Fair," and "Poor."

2.1.6 Cost. The "total cost" of an upstream facing system must include other costs besides the cost of installing or constructing the upstream face. Additional costs to be considered include: (1) construction coordination and inspection costs paid by the owner, (2) the cost of delays that the system may have on production rates of other work items, (3) the cost of limiting the range of RCC construction methods such as the sloped RCC placement method, or constructing the dam in monoliths, (4) the additional cost of financing the project or lost revenue if installing the facing system delays filling the reservoir, (5) maintenance and replacement costs, (6) patent or royalty fees, and (7) savings that the facing system may have on the design of the dam due to uplift reduction.

2.1.7 Facing System Impact on Structural Stability and RCC Mix Design. The U.S. Army Corps of Engineers' (Corps) current design standards for evaluating uplift within gravity dams, including RCC dams, is presented in EM 1110-2-2200 – Gravity Dam Design (U.S. Army Corps of Engineers, 1995). For conventional concrete dams, uplift within the body of the dam is assumed to vary linearly from 50 percent of maximum headwater at the upstream face to 50 percent of tailwater, or zero, as the case may be, at the downstream face. This guideline accounts for the relative impermeability of intact concrete which precludes the buildup of internal pore pressures. The Corps notes, however, that cracking at the upstream face or weak horizontal construction joints in the body of the dam may affect this assumption. For RCC dams, the Corps stipulates that the uplift within the dam is a function of the permeability of the facing system and the properties of the RCC. The Corps cautions that a porous upstream face and lift joints in conjunction with an impermeable downstream face could result in a pressure gradient through a cross section of the dam considerably greater than that outlined above for conventional concrete.

When drilled drains are installed in the foundation or within the body of the dam, their effectiveness is assumed to vary from 25 to 50 percent. When performance of the drainage system can be verified, the effectiveness of the drains can be increased to a maximum of 67 percent.

Facing Systems with Fully Drained Face. Internal uplift reduction can be achieved with facing systems that provide a drainage layer on the downstream side of the facing system, such as an external geomembrane liner with a geonet drainage layer, or precast panels and an internal geomembrane liner and drainage layer. This type of facing system is normally installed on the upstream face of dams to eliminate seepage through the dam and "dehydrate" the body of the dam to prevent freeze-thaw damage. The drainage system installed with this system can be verifiable and has been proven to perform as intended. Using a facing system that has a fully drained face, 100 percent uplift reduction is likely at the upstream face of the dam; however, a 50 percent uplift reduction is probably appropriate for design. The full benefits of this system, however, cannot be realized unless the same uplift reduction can be achieved in the foundation. That is, the cross section or dimensions of the RCC

Figure 2.1. Installation of drainage layer to create fully drained face, (photo courtesy of CARPI).

dam to achieve adequate structural stability will be governed by the maximum uplift reduction achieved in the foundation through grouting and installation of a foundation drainage system. Although not recommended, benefits of a substantial uplift reduction at the upstream face could include eliminating drilled drain holes in the body of the dam, relaxation of lift quality and treatment standards, eliminating construction of contraction joints in the dam, and savings in the RCC mix used to build the dam. Using this facing system and including the aforementioned features in the dam, the factors of safety for stability within the body of the dam will be conservatively high.

Facing Systems without Fully Drained Face. Internal uplift reduction for facing systems that do not have a fully drained face, such as a conventional unreinforced and reinforced concrete face, depends primarily on the watertightness of the face, permeability of the RCC, and internal dam drainage. Without a face drain and adopting current design guidelines for concrete dams, a reinforced conventional concrete face with waterstopped joints can result in a 50 percent reduction in uplift at the face of the dam by accounting for the relatively high impermeability of the reinforced concrete. Additional reduction in uplift pressure can be achieved by drilling drains within the body of the dam a short distance from the upstream face or by installing strip drains on the face of the RCC dam concurrent with RCC placement, or just prior to placing the reinforced concrete. Like the geomembrane systems, the full benefits of this system cannot be realized unless the same uplift reduction can be achieved in the foundation.

For formed RCC and formed unreinforced conventional concrete facing systems, the Corps stipulates that the determination of the percent of uplift pressure depends on the RCC mix permeability, lift joint treatment, placement techniques specified for minimizing RCC segregation, RCC compaction methods, and the treatment for watertightness at the upstream and downstream faces. Construction of a test section in accordance with EM 1110-2-2006, Roller-Compacted Concrete, can be used as a prototype for determining the permeability of the RCC facing system, thereby providing some guidance on uplift distribution for use by the designer.

2.2 Description of the Most Popular Upstream Facing Systems

2.2.1 General. Although 17 upstream facing systems have been used worldwide, for discussion these systems can be categorized into nine basic types of facing systems. Variations within each type of facing system are discussed along with their generally accepted advantages and disadvantages.

2.2.2 Formed/Exposed RCC. This upstream facing system simply consists of forming the RCC face with conventional removable forms. It is generally selected for dams where seepage and aesthetics are not a concern. The dams presented in Table 1.2 where this upstream facing method was used are mostly flood control or stormwater detention dams and tailings dams where there is no permanent impoundment. The tallest RCC dam constructed with this facing system is Shibanshui Dam in China at a height of 285 feet. The tallest dam in the United States with this facing system is Bullard Creek Dam in Oregon at a height of 52 feet. In some cases the upstream face is formed against a concurrently placed earthfill berm or existing smaller earthfill dam.

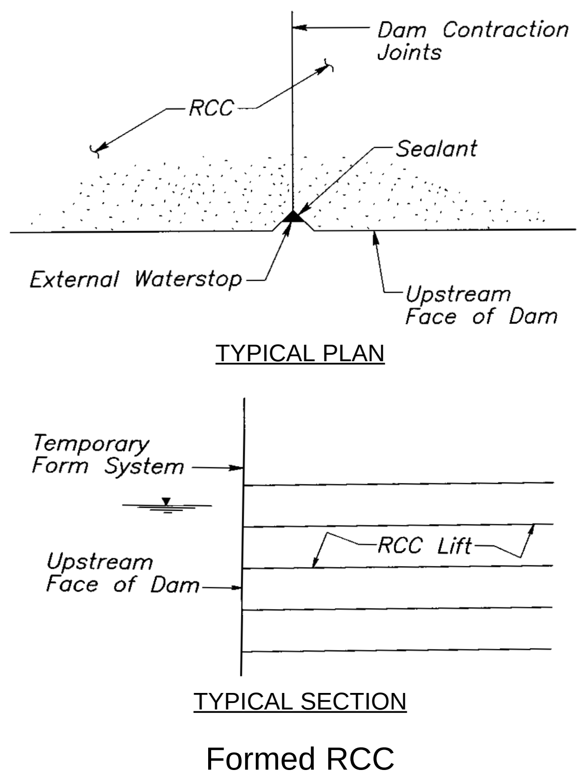


Figure 2.2. Typical plan and section of formed/exposed RCC upstream facing system.

ACI Committee 207 addresses RCC permeability in Roller-Compacted Mass Concrete (ACI, 1997). As noted in the report, permeability of RCC is dependent upon the voids in the compacted mass together with porosity of the mortar matrix, and therefore is almost totally controlled by mixture proportioning, placement method, and degree of compaction. When care is taken to proportion and compact the RCC, the permeability of the RCC should be similar to that of conventional mass concrete. Test values for RCC permeability range between $0.3x10^{-9}$ to $30x10^{-9}$ feet per minute. If seepage occurs in RCC dams, it is usually along the horizontal lift joints, uncontrolled cracks, or monolith joints, rather than through the compacted mass. The best method of minimizing seepage is to install contraction joints at strategic locations transverse to the dam axis, installing waterstops at the transverse contraction joints, and using bedding mortar between horizontal RCC lifts within a zone at the upstream face of the dam. Seepage through RCC dams has also been found to gradually decrease with time as horizontal lift and contraction joints are filled by sedimentation and calcification. Lift joint permeability can be decreased by using bedding mortar between the lifts and chemical grout or other sealants to seal contraction joints at the upstream face after construction. Most designers who are concerned with minimizing seepage through the dam will not use this facing method alone.

Figure 2.3 Formed RCC (below average quality).

The appearance of the exposed RCC face can be improved by using an RCC mix with smaller aggregates and a low vebe time. An example of an RCC dam with an above average quality formed RCC face is Bullard Creek Dam in Oregon. Exposed RCC in harsh climates where freeze/thaw cycles occur can experience varying degrees of weathering. The rate of weathering may appear rapid at first; however, it should dramatically decrease with time. This is primarily due to the fact that it is difficult to achieve a high degree of compaction near the base of the lift when RCC is placed directly against formwork. This results in lower density and lower strength at the exposed face. As weathering progresses, the lower strength, less dense, and therefore weaker RCC sloughs away from the exposed surface; the stronger, more resistant RCC becomes exposed. To improve the density and surface appearance at the exposed face, a wedge or fillet of bedding mix can be placed against the form prior to placing the RCC. The dozer operator can spread the RCC against the form in a manner which causes the bedding mix to ride up the face of the form. If the RCC is then carefully compacted, the texture of the finished face can approach that of conventional concrete; however, this is difficult to achieve on a continuous basis.

Figure 2.4. Formed RCC (above average quality) Bullard Creek Dam, OR, (photo courtesy of Benjamin Doerge).

In a reservoir environment, most weathering of the upstream face will occur at and above the waterline where there is exposure to wave action, wind, and greater temperature variations. The rate of deterioration is a function of the climate, the RCC mix design properties, aggregate quality, cement content, and the degree of compaction achieved at the face. Typically, greater strength of the mix and aggregates produce greater durability.

Advantages of this facing system are that it involves routine construction procedures except for waterstop installation, does not impede or otherwise complicate RCC placement, and is the most economical facing system. Disadvantages include marginal seepage control, rough unfinished appearance, and sometimes poor durability in moderate to severe climates.

2.2.3 Formed Unreinforced Conventional Concrete. This is the most popular upstream facing system used on RCC dams, and has been used on 132 of the 214 dams constructed worldwide. There are several

Figure 2.5. Elk Creek Dam, OR.

variations of this facing system. The first generation of this type of facing system had no vertical crack control joints or only widely spaced joints. This method was used at Elk Creek Dam in Oregon where watertightness comparable to that of a conventional concrete gravity dam was desired. The method involved first placing a thin, 1/4- to 1/2-inch, layer of bedding mortar evenly over the entire lift surface just ahead of the dozer spreading the RCC for the next lift. Later it was concluded that the necessary watertightness between lifts could have been achieved by placing the bedding mortar on the upstream 1/3 portion of each lift (Hopman, 1992). The upstream face of the dam used forms tied to the dam with steel tie bolts. A 2-foot lift of RCC was then placed to within 3 feet of the upstream form. The 3-foot wide zone between the upstream form and the placed RCC was then filled with air-entrained conventional concrete having a 3-inch maximum size aggregate. This zone of conventional concrete was intended to provide a “first line” defense against water leakage through the structure (Hopman, 1992). The 3-foot wide zone of conventional concrete was consolidated using emersion type vibrators. Waterstop was installed in the conventional concrete at the full dam height at vertical transverse contraction joints. The transverse contraction joints were installed with a maximum spacing of 300 feet across the 2,580-foot-long dam.

Construction of Elk Creek Dam was halted after 348,000 cubic yards of the total 1,041,000 cubic yards of RCC were placed. During this shut down period an evaluation of the upstream facing method was performed. It was concluded that this upstream facing system was costly and slow to construct, and did not fit well with the other fast track construction operations. Problems included: coordination of the conventional concrete placement with the RCC placement, concentration of pockets of segregated RCC at the bottom of the interface between the RCC and conventional concrete, and lack of continuous consolidation of the RCC/conventional concrete interface. Core drilling and water testing at the interface between the conventional concrete and the RCC showed that voids along the interface could interconnect facing cracks and contraction joints and act as a conduit for seepage (Hopman, 1992). It was decided that prior to resuming construction of Elk Creek Dam, changes would be made to the specifications to tighten procedural requirements for consolidation of the RCC/conventional concrete interface and to reduce the maximum size aggregate of the conventional concrete from 3 inches to $1\frac{1}{2}$ inches. However, before improvements to construction techniques to the upstream facing system could be fully implemented and further evaluated, final construction of Elk Creek Dam was terminated due to environmental issues.

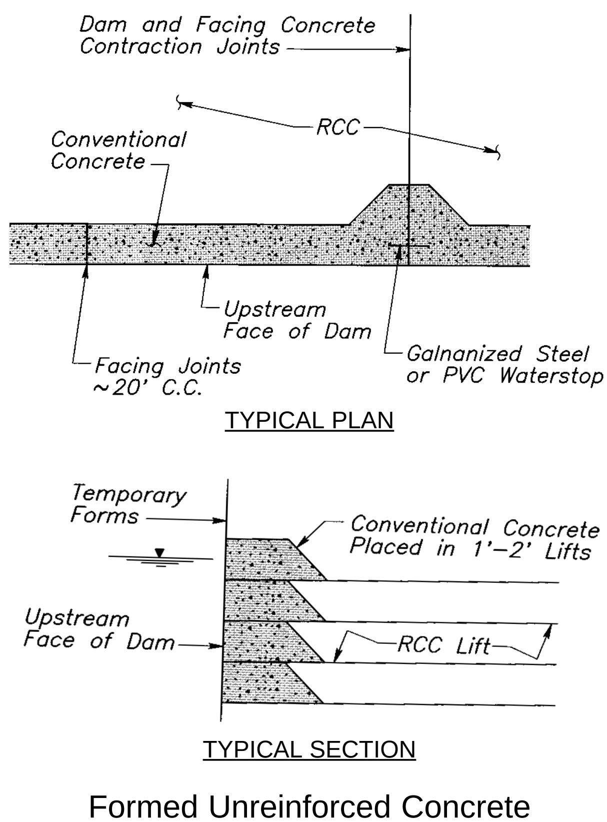


Figure 2.6. Typical plan and section for formed unreinforced conventional concrete upstream facing system.

A second-generation variation of this facing system involved installing closely spaced joints within the face, and has been the most commonly used variation of this facing method. A consensus has not been reached with regard to the lateral width or thickness of conventional concrete at the upstream face or whether it should be placed before or after the adjoining RCC lift. The lateral width of conventional concrete normally ranges between 1 to 3 feet; however, RCC dams in Japan have used a layer as wide as 10 feet (Hansen, 1991). Wide thermal cracking is reduced to hair-line fractures by including notches and / or closely spaced control joints or crack inducers in the facing concrete between dam contraction joints 10 to 20 feet on center, extending from the top to the bottom of the dam.

For Stagecoach Dam in Colorado, two alternatives for the facing system were included in the contract bid documents: (1) an 18-inch thick cast-in-place conventional concrete face with closely spaced crack control joints, and (2) precast concrete panels with a geomembrane liner. Based on bids received, the cast-in-place facing system was selected. It was reported that the precast concrete panels with a liner would have added approximately 4.4 percent to the total construction cost (Arnold, 1992). At Stagecoach Dam, bedding mortar was placed in a 12-foot wide zone at the upstream end of each RCC lift. Crack inducers in the facing concrete were constructed at 10-foot centers using vertical strips, 1.5 inches deep and 0.75 inches wide. These slots were later filled with a backer rod and AquataPoxy sealant. After completion of the dam, narrow cracks were observed in the facing concrete. All of the cracks occurred within the crack-inducer strips. Total seepage from the gallery, including abutment drains, is reported to be less than 25 gal / min (Arnold, 1992). Natural seepage reduction has been observed due to silt and calcification filling the seepage paths.

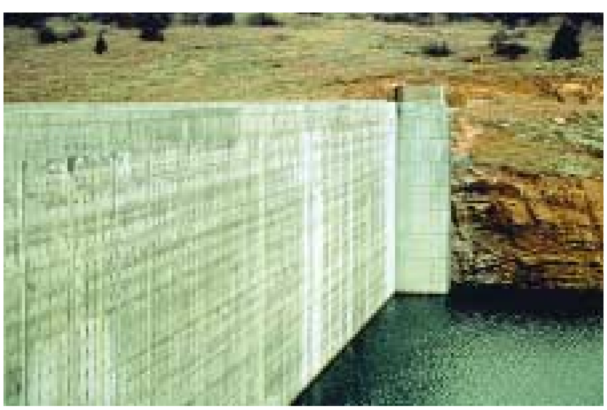


Figure 2.7. Upstream face of New Elmer Thomas Dam, OK.

Figure 2.8. Vertical notch with sealant, New Elmer Thomas Dam, OK.

At New Elmer Thomas Dam, similar crack-control notches were formed in a 2.5-foot wide cast-in-place conventional concrete face. Bedding mortar was placed in a 10-foot wide zone at the upstream end of each RCC lift surface. Vertical notches were also spaced at 10-foot centers and extended the full height of the dam. A water-expandable seal and a polymer seal were placed in the notches to prevent water seepage into the upstream face through the notches (Figure 2.8) (Choi, 1994). At Monksville Dam, waterstopped vertical joints were placed in the facing concrete every 20 feet as shown in Figure 2.9.

Figure 2.9. Installation of waterstop at vertical joints, Monksville Dam, NJ.

Figure 2.10. Formed unreinforced conventional concrete face of Monksville Dam, NJ.

As previously noted, horizontal construction joints in conventional concrete can have high permeability due to cold joints and/or drying shrinkage in concrete. Temperature shrinkage-induced cracking commonly occurs in unreinforced conventional concrete that is restrained at one face and exposed on the opposite face. Cold joints and cracking increase the facing's permeability. Drying and temperature shrinkage-induced cracking are difficult to control for this facing system. Installation of waterstops at transverse contraction joints is often difficult to perform during construction and these waterstops have been suspected as the source of seepage at some dams. Drainage for the purpose of relieving pore pressure within the RCC mass downstream of the upstream facing system is generally provided by drilling inclined or vertical drain holes during or after construction from the top of the dam and/or gallery. Trout Creek Dam in Colorado was the first to incorporate horizontal waterstops at the end of each day's placement. On average, the waterstop was placed in every third or fourth lift.

Figure 2.11. Waterstopped contraction joint at Quail Creek Dam, UT.

Figure 2.11 shows a typical waterstopped dam contraction joint at Quail Creek Dam in Utah.

Advantages of this facing system include readily available construction materials, no additional installation time requirement after RCC placement, and the durability and attractiveness of the exposed face if attention is paid to setting the forms and properly consolidating the conventional concrete. Disadvantages include the need to coordinate multiple construction materials and activities that are time-critical. The production, delivery, and placement of the conventional concrete must be completed within a limited time frame (30-45 minutes) concurrent with RCC placement in order to ensure adequate bond at the conventional/RCC interface within the initial set times of the two materials. In addition, conventional concrete placing equipment further congests the lift surface, waterstops are not easily installed at contraction joints, horizontal joints may not be watertight, the face is prone to cracking because of differences in elastic and shrinkage properties from those of the RCC, consolidation at the conventional concrete and RCC interface can be difficult to achieve, and sealants placed in crack inducing joints tend to separate from the concrete.

The tallest dam in the world to use this facing system is Miyagase Dam in Mexico at a height of 508 feet. The tallest dam in the United States with this facing system is Monksville Dam in New Jersey at a height of 157 feet.

2.2.4 RCC Against Precast Panels Without A Liner. Willow Creek Dam in Oregon was the first RCC dam constructed in the world and, therefore, the first to use this upstream facing system. The tallest dam in the world constructed with this facing system is Shuidong Dam in China at a height of

Figure 2.12. Typical dam section showing RCC against precast panels.

187 feet. This "First Generation" upstream facing method provided an innovative means of forming the upstream face with an economical stay-in-place form which is both durable and aesthetically pleasing, but by itself does not reduce the potential for seepage through the dam. Although Willow Creek Dam was designed to be stable with full uplift pressure along each horizontal lift joint, the seepage which emerged from the lift joints at the downstream face of the dam during filling of the reservoir was found to be undesirable. This condition can be mitigated by providing internal drains to intercept the seepage before it reaches the downstream face of the dam. This facing system has been repeated at three dry detention dams: Cuchillo Negro Dam in New Mexico, Zintel Canyon Dam in Washington, and Reichs Ford Dam in Maryland. For Zintel Canyon Dam (Figure 2.14) it was reported that using the precast panels to form the upstream face of the dam was less expensive than placing a conventional concrete facing against movable temporary formwork (Hansen, 1994).

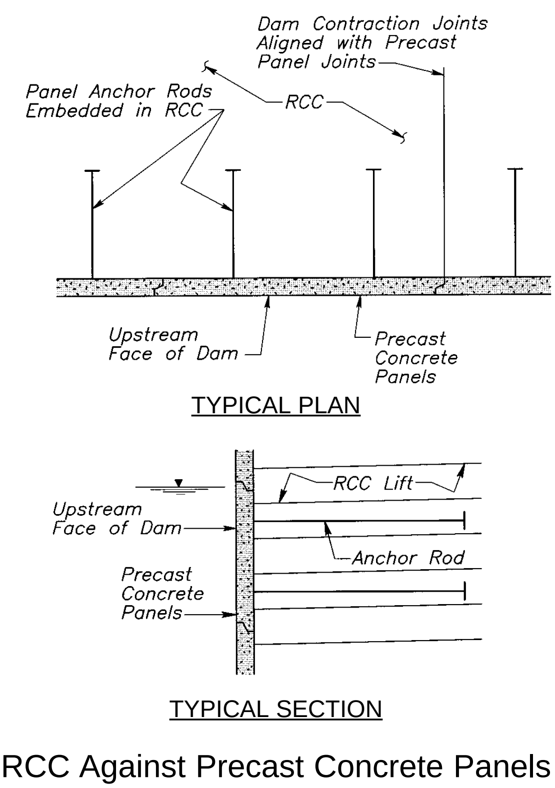


Figure 2.13. Typical plan and section of RCC against precast concrete panels.

The most common size of the unlined precast panels is 4 feet high, 16 feet long and 4 inches thick. Panels are normally erected by first bracing them with exterior strongbacks (Figure 2.15) and then threading steel anchor rods into inserts located in the downstream face of the panels. Typical 4'x16' panels have 4 anchor bars each with a pullout resistance of 10,000 lbs. The anchor rods are embedded into the RCC as lift placement progresses. After previously placed RCC lifts progress to sufficient height and strength, anchor rods installed in lower panels provide support for the upper panels through the external strongback system as subsequent lifts of RCC are placed. To improve the density and watertightness of the RCC at the upstream face, a wedge of bedding mix can be placed against the downstream face of the panel prior to placing the next RCC lift. The dozer operator can spread the RCC against the panel/form in a manner which causes the bedding mix to ride up the face of the panel.

Figure 2.14. Upstream face of Zintel Canyon Dam, WA.

Variations of this system have included the placement of low-slump conventional concrete between the RCC and the panels to improve impermeability at the upstream face of the dam. The conventional concrete and RCC are consolidated in an attempt to provide a monolithic joint at the interface. The conventional concrete at the upstream face acts as the seepage barrier. Horizontal construction joints in the conventional concrete, however, can still have high permeability due to cold joints and/or drying and temperature shrinkage in concrete. The tallest RCC dam in the world to use this variation is Trigomil Dam in Mexico at a height of 329 feet, with Spring Hollow Dam being the tallest in the United States.

Figure 2.15. Upstream face of Penn Forest Dam, PA showing support of precast panels using strongbacks.

Precast panels can be installed with several alignment options. Precast panel alignment options include:

1. Both horizontal and vertical panel joints are aligned (North Fork Hughes River Dam)
2. Horizontal joints aligned with vertical joints staggered (Penn Forest Dam, Big Haynes)
3. Vertical joints aligned with horizontal joints staggered (Zintel Canyon Dam, Siegrist Dam)

In general, panels that are aligned horizontally can be installed faster because each panel simply abuts against the other in a continuous row. When panels are aligned vertically, each panel must be fitted between two adjoining panels, and, if tolerances are not met, this can be difficult. Regardless of the alignment option selected, the panel anchor rod holes must line up vertically so that a strongback support system can be used. In addition, the vertical panel joints must line up with the dam contraction or monolith joints. This requires use of half panels at contraction joints if vertical panel joints are staggered.

Advantages of this facing system include a durable and attractive finished face, and no additional installation time requirement after RCC placement. Disadvantages can include excessive seepage, and the need to coordinate an additional construction material and activity that is time-critical in the use of the low-slump conventional concrete variation. Removing "out of specification" RCC is complicated by anchor rods embedded in the RCC.

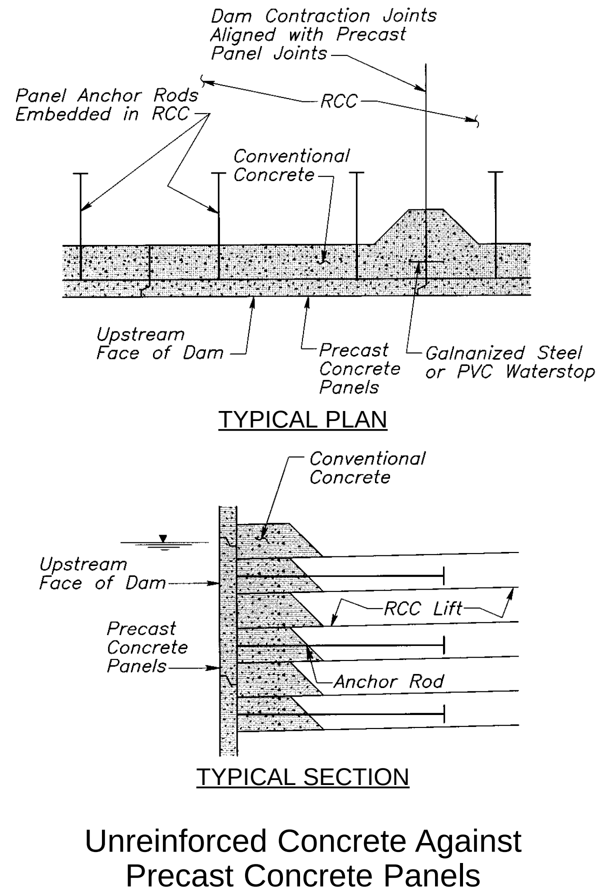


Figure 2.16. Typical plan and section of unreinforced conventional concrete against precast panels upstream facing system.

This facing system led to a very successful "Second Generation" upstream facing method which includes an impervious liner attached to the downstream face of the panel.

2.2.5 RCC Against Precast Panels With An Internal Liner. This popular second generation system uses the first generation precast panel system with the addition of a liner to provide a watertight seepage barrier. In most cases the liner material is a 65-80 mil thick PVC material. However, low density polyethylene (LDPE) liner material was successfully used at Christian E. Siegrist Dam and high density polyethylene (HDPE) has been used on other projects. The first five dams in the U.S. to use this method were Winchester Dam, Christian E. Siegrist Dam, Spring Hollow Dam, Hudson River

11 Dam, and Big Haynes Dam. They relied on a "T-Lock" surface anchor system manufactured by Poly Tee and Ameron in the United States to attach the sheets of liner material to the downstream side of the panels. Except for Big Haynes Dam, these dams used the common panel size of 4 feet high, 16 feet long and 4 inches thick. The tallest dam in the world to use this method is Spring Hollow Dam in Virginia at a height of 240 feet.

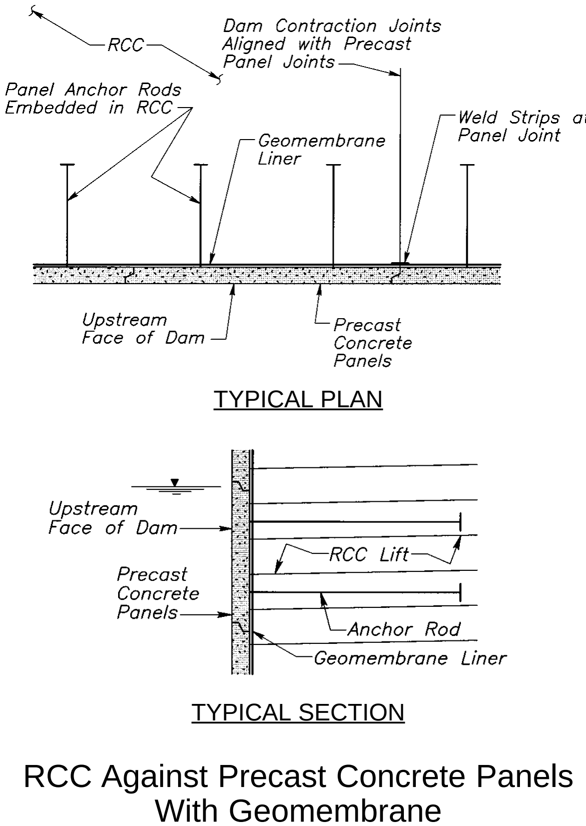


Figure 2.17. Typical plan and section of RCC against precast concrete panels with liner upstream facing system.

The two most recent RCC dams to use this method, Penn Forest Dam and Buckhorn Dam, used an alternate method of attaching the sheets of liner material. The PVC liner material (Sibelon CNT 2800) was manufactured by CARPI of Italy, and consists of an 80 mil thick high performance PVC coupled with a non-woven geotextile. The liner is attached to the panels by first placing fresh concrete into the casting bed, followed by rolling and vibrating the liner material onto the exposed concrete surface of the panel with the geotextile side of the material placed on the fresh concrete (Figure 2.19). The liner remains attached to the panel through the bond made by the absorption of concrete paste into the geotextile material.

This method of attaching the PVC liner to the precast panels was initially tested for the Penn Forest Dam project by pulling apart several panels partially connected by PVC joint strips welded to the liner material on each adjacent panel. The destructive testing demonstrated that the stress concentrations in the PVC liner material did not concentrate at the welds between panels, but became distributed within the liner over much of the panel area. It was observed that as the panels were pulled apart, the bond between the geotextile and the PVC liner failed first, allowing the liner material to behave elastically and stretch more than 18 inches at the joints before failing. This method of liner attachment offers several benefits over the traditional "T-Lock" surface anchor system for liner attachment, including: greater flexibility, improved liner elongation, and better resistance to stress concentrations. Both the "T-Lock" and CARPI systems have been successful. The selection of the type of geomembrane to use depends on specific project requirements.

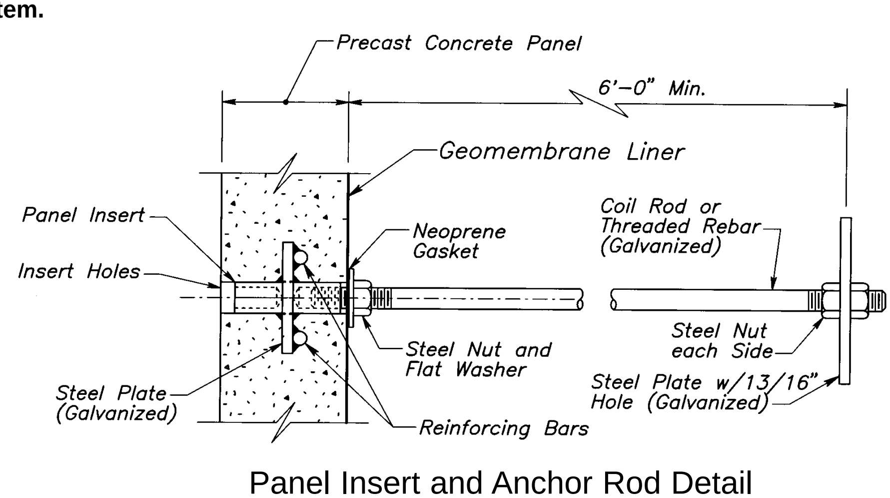


Figure 2.18. Typical panel insert and anchor rod detail.

Figure 2.19. Photographs showing casting of precast panels with internal liner (left) and destructive testing of liner weld between two precast panels for Penn Forest Dam, PA.

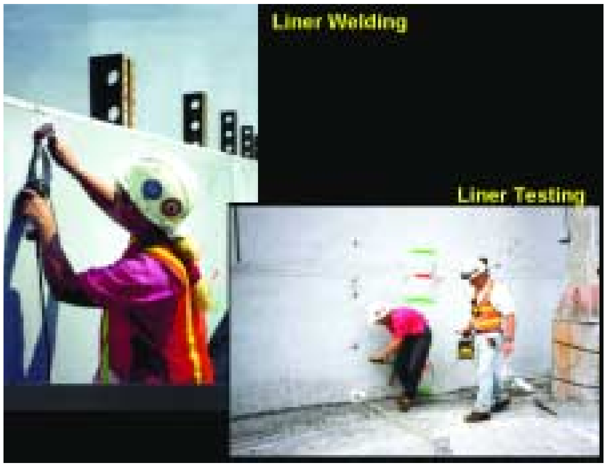


Figure 2.20. Liner welding and testing at Penn Forest Dam, PA.

At Penn Forest Dam the first rows of panels were 4 feet high and 16 feet long. Later, the contractor exercised a contract option to increase the height of the panels to 6 feet. Using larger panels decreased the time required to place panels, and reduced the total length of heat-welded horizontal and vertical PVC liner joints by approximately 35 percent. The total length of liner joint welding on Penn Forest Dam was approximately 10 miles. The task of welding the liner joints can be time consuming, must be performed by certified welders, and adds to the total cost of the facing system.

The largest panel size used on an RCC Dam is 7.2 feet high, 16.4 feet long, and 4 inches thick. Panels of this size were used on the 253-foot-high Urugua-I Dam in Argentina.

Figure 2.21. Construction photo of upstream face of Penn Forest Dam, PA.

A variation of this facing system is to place unreinforced conventional concrete between the lined panels and the RCC as shown in Figure 2.16. With the benefits to durability and watertightness already provided by the precast panel and liner material, respectively, the need for conventional concrete, however, is questionable from a technical standpoint and increases the overall cost. Conventional concrete was used at Hudson River Dam in Georgia.

The integrated precast concrete panel and liner system, commonly referred to as the "Winchester Method," is patented and payment of royalty fees is required when it is used. On Penn Forest Dam the total panel area for the upstream face of the dam is approximately 230,000 ft². Patent fees were approximately $0.40/ft². The patent for the Winchester Method (U.S. Patent 4,659,252) was issued on April 21, 1987 and is owned by Donald L. Sexton et al. of Perrott, Ely and Hurt Consulting Engineers, Inc. CARPI has the rights to this patent both inside and outside of the United States.

Two more recent RCC dams designed with this upstream facing system include North Fork Hughes River Dam in West Virginia, and Hunting Run Dam in Virginia. During the bid phase for Hunting Run Dam, contractors were required to submit bids for two facing systems: RCC against precast panels with a liner, and reinforced conventional concrete placed after RCC construction. The bids received from all of the contractors for the precast panel facing system were lower than the bids for the reinforced concrete facing system. The low bid accepted for construction of the dam was $18.76 million versus $19.53 million for the dam with the reinforced concrete facing system. This represents a difference of $765,000 between the two facing systems, or approximately $6.47 per square foot for the 118,200 ft² face of this dam. The contractor for Hunting Run Dam elected to use a larger and thicker precast panel than that which was originally specified in the contract with the contractor's alternate having dimensions of 6 feet high, 16 feet long, and 5 inches thick.

Advantages of this facing system include a durable and attractive finished face, excellent seepage control, protection of the liner from ultra-violet radiation exposure and vandalism, and no additional installation time required after RCC placement. Disadvantages include the need for intense inspection of liner welds and panel anchor installation, and occasional difficulty controlling panel alignment.

Figure 2.22. Slip-formed facing, Upper Stillwater Dam, UT.

2.2.6 RCC Against Slip-formed Facing Elements. The only two examples of a dam in the United States which used this innovative method are Upper Stillwater Dam in Utah and Town Wash Dam in Nevada. The cast-in-place upstream facing for Upper Stillwater Dam was constructed using a laser-guided slipform curbing machine. This facing system was primarily intended as a forming method and means of protecting the RCC from severe weather, rather than as a seepage reduction measure (Moler, 1988). The 2-foot-high interlocking curbs were constructed of 0.5-inch-slump conventional concrete in continuous lengths from 500 feet at the base to 2673 feet at the crest. Each curb element required 4 hours to set before RCC could be placed against the element. Challenges encountered with this system included controlling line and grade, excessive slumping of the placed elements, and some delays in RCC placement while the placed elements were curing. A total of 98 miles of slip-formed elements were placed requiring a total of 87,000 cubic yards of concrete (Hansen, 1991). Horizontal and vertical tolerances of 1½ inch were maintained during construction. No contraction joints were formed in the RCC or the slip-formed elements during construction. At Town Wash Dam, the curb was placed only one foot high.

During first filling of Upper Stillwater Dam, a 0.26-inch-wide crack appeared in the dam, producing about 1,300 gal/min leakage into the gallery and about 1,800 gal/min leakage from the crack on the downstream face (Smoak, 1991). The crack extended from the foundation to the crest of the dam and from the upstream face to the downstream face. The crack was believed to be a result of high thermal stress induced during RCC cooling and foundation deformation. Similar but smaller cracks

Figure 2.23. Casting of slip-formed facing element.

developed at three other locations. The total seepage from all the cracks in the dam was over 3,000 gal/min. The selected repair procedure involved injecting polyurethane resin into the cracks. After grouting the cracks in 1990, total leakage through the cracks was approximately 800 gal/min. Treatment to further reduce leakage was planned, including the possibility of installing an external liner/waterstop system over the crack.

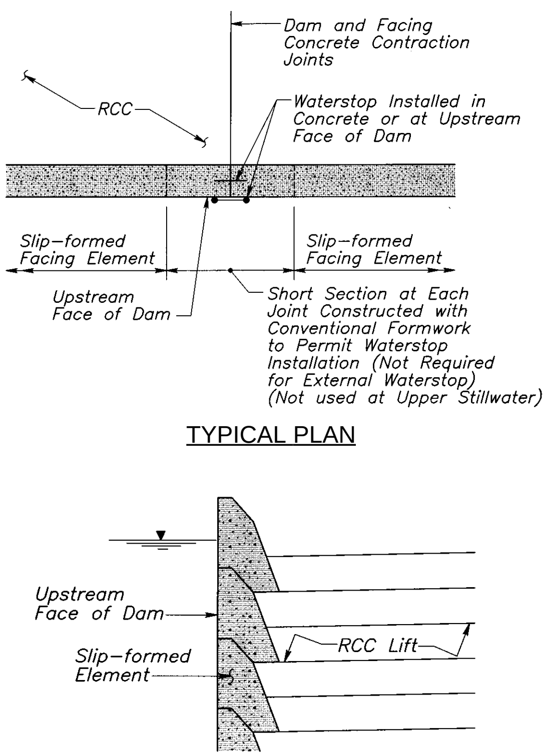
An important finding from the performance evaluation of Upper Stillwater dam is that RCC dams should incorporate waterstopped contraction joints to avoid development of uncontrolled transverse cracks (Richardson, 1992). For small dams with short crest lengths or for large dams constructed monolithically, this system is not practical since construction of the facing elements will impede RCC construction. Porce Dam II in Columbia with a crest length of 1,400 feet and a height of 403 feet is the tallest RCC dam in the world to use this facing system.

Advantages of this system include a facing system that has a durable finish and requires no additional installation time after RCC placement. Disadvantages include cracking because of differences in elastic and shrinkage properties of the conventional concrete from those of RCC, difficulty in controlling concrete slump to required ±1/4-inch tolerance, complicated construction of contraction joints, the presence of a slip-form machine and ready mix trucks on the lift surface, and horizontal cold joints every 1 to 3 feet vertically that may not be watertight.

2.2.7 Reinforced Conventional Concrete Against Formed RCC. This facing system is an adaptation of the modern facing system used on concrete-faced rockfill dams (CFRDs). It involves placing a reinforced concrete facing against the upstream face of the dam after RCC placement is completed. Steel anchors, embedded in the RCC, support the reinforced concrete facing. Steel reinforcement is placed at both faces and in each direction to control thermal and shrinkage cracking. Waterstops are installed at every construction and contraction joint.

Two dams have been constructed in the United States using this facing system: SW Freese Dam (Stacy Dam) and Lake Alan Henry Dam, both in Texas. No seepage from the RCC has been reported. This system was selected over precast panels with a geomembrane liner because of concerns that wave action on these reservoirs, which have a large fetch, might eventually damage the precast panels (Lemons, 1994). The tallest RCC dam constructed with this facing system is Longmentan Dam in China at a height of 190 feet.

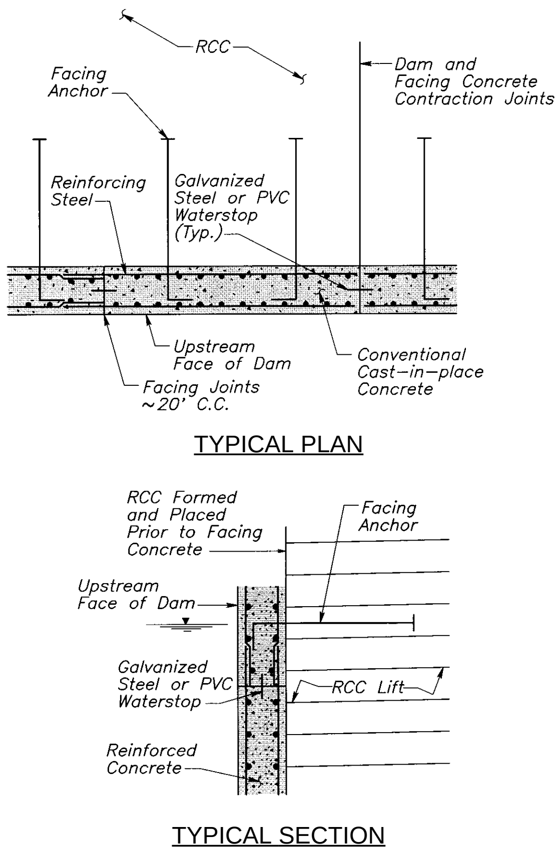
Although there are only four RCC dams in the world constructed with this upstream facing system, there are over 300 concrete-faced rockfill dams



TYPICAL SECTION (Upper Stillwater)

RCC Against Slip-Formed/Extruded Facing Elements

Figure 2.24. Typical plan and section of RCC against slip-formed/extruded facing elements upstream facing system.



Reinforced Concrete Placed Against RCC

Figure 2.25. Typical plan and section of reinforced concrete placed against RCC upstream facing system

either constructed or in planning stages worldwide. Concrete-faced rockfill dams have been built over 700 feet high. Recent trends in face slab design indicate that the current practice is to set the slab thickness equal to *1 foot + 0.002 x (dam height)* (Cooke, 1998). For CFRDs less than 300 feet high, uniform slab thicknesses of 9 to 12 inches have often been adopted. For practical placement against a vertical face, a minimum thickness of 18 inches is recommended. For very high dams, the controlling criterion is the thickness that is needed to safely resist shear and bending of the cantilevered portion of the slab on each side of the waterstop at the joints (Schrader, 1995).

Concrete is normally formed in panels approximately 20 feet long by 10 feet high using conventional forming methods. Appearance of facing concrete completed on existing RCC dams is good. Seepage control and durability has also proven to be good provided adequate quality control measures are taken during concrete mixing and placement. A curtain of equally spaced vertical drain holes can be drilled a short distance from the upstream face within the body of the RCC dam to reduce pore pressure. An alternative drain system would be to install strip drains on the face of the dam concurrently with RCC placement or just prior to casting the reinforced concrete face.

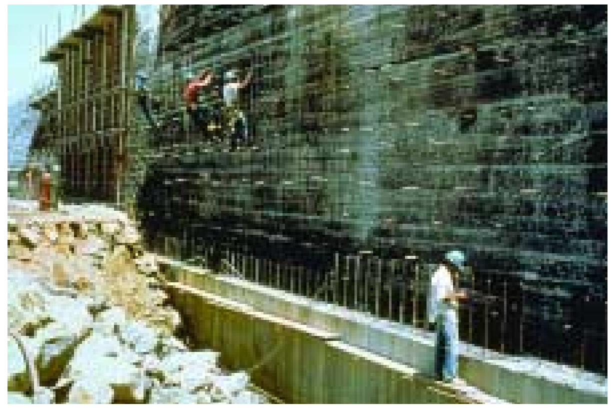


Figure 2.26. Freese Dam, TX.

The reinforced concrete facing system is best installed during cool weather to minimize the potential for temperature cracking as the concrete cools. However, additional measures such as increased reinforcement, pre-cooling of concrete, and use of water-reducing admixtures can be incorporated to compensate for placing the concrete during warm weather.

Waterstops are generally available in two material types: metallic and non-metallic. Metallic waterstops are normally made of copper, stainless steel, or galvanized steel, and are used in large dams where strength rather than flexibility is needed, and very little movement at the joints is expected. Non-metallic waterstops are normally composed of a synthetic rubber such as PVC, and provide flexibility rather than strength. They must possess good extensibility, recovery, chemical resistance, and fatigue resistance. An adhesive bond is formed between the metallic waterstop material and the concrete. Non-metallic waterstops such as PVC rely on a mechanical bond or interlock formed with the concrete and ribs or bulbs of the waterstop rather than a chemical or adhesive bond. Either metallic or non-metallic waterstops can be used. If non-metallic (PVC) waterstops are used, they should be non-tapered, with a 12-inch width, having a minimum 1/2-inch thickness with serrations or ribs and a center bulb. Factory fabricated T's, L's and Crosses should be used to ensure quality of splice welds. Hog ring or grommet fasteners spaced at 12 inches on center should be used to keep the waterstop in place during concrete placement. For the upper portion of the dam or relatively low dams subject to less hydrostatic head, consideration could be given to reducing the size and thickness of the waterstop.

Waterstops must be installed at the perimeter joint along the foundation and at every contraction joint in the dam. One of the principal causes of leakage in CFRD's has been the faulty installation of the waterstop and placement of face concrete. Current CFRD practice is to continue longitudinal reinforcing through the vertical joints without waterstops. This is considered good practice, is more economical, and has been adopted on many CFRD's (Cooke, 1987). Waterstops are not used in CFRD face-slab horizontal construction joints (Cooke, 1987).

Advantages of this system include an attractive durable appearance, easily installed joints to accommodate expansion and contraction, the potential for crack-control through reinforcement, the lack of a requirement for bedding mix or higher cementitious content in the RCC mix for seepage control, the lack of interference from facing operations during RCC placement, and the easier control of materials since construction is independent of RCC placement. Drawbacks include a longer construction period and higher construction costs. As previously noted in the discussion for the precast panel facing system with an internal liner, Hunting Run Dam in Virginia received bids for both facing systems. The low bid for the precast panel facing system was approximately $6.47 per square foot less than the low bid for the reinforced concrete facing system. This example is considered indicative for most cases.

2.2.8 Formed RCC with External Liner. Galesville Dam is the only RCC dam in the United States constructed using this type of upstream facing system. At Galesville Dam, the liner consisted of a coal-tar-based elastomeric membrane that was sprayed on the upstream face in two 20-mil-thick layers. When the reservoir was filled, seepage occurred through several transverse cracks in the dam. The spray-on coating did not effectively bridge the cracks, but did reduce seepage through the area between the cracks. Seepage was subsequently reduced by having underwater divers caulk the cracks with a quick-set cement. Painting or spraying a waterproof coating onto the upstream face of a dam is usually dismissed as being nonpermanent and impractical to tie into the foundation. There are also concerns about moisture being trapped between the membrane and the concrete facing, resulting in saturation of the concrete and damage from freezing (Schrader, 1985).

The external liner is normally installed after the dam has been fully constructed. Many external liner facing systems have been tried on the vertical faces of concrete dams including: shotcrete, metal sheets, bituminous liners, spray-on geomembranes, and synthetic geomembrane in rolls or sheets. The seven main types of geomembranes include:

1. Polyvinyl Chloride (PVC)
2. High Density Polyethylene (HDPE)
3. Chlorosulfonated Polyethylene (CSPE)
4. Chlorinated Polyethylene (CPE) - commonly called Hypalon
5. Butyl (rubber)
6. Polypropylene (PE)
7. Bituminous Geomembranes

Over the last six years several agencies with international reputations for excellence in dam design have expressed an interest in using geomembrane facing systems as a repair method for aging concrete gravity dams. Both Hydro-Québec and the U.S. Army Corps of Engineers have performed significant research to evaluate the performance of various geomembrane systems. In addition, the Enté Nazionale Energia (ENEL) of Italy and Electricité De France have installed upstream geomembrane facings on both new and aging concrete gravity dams, and have performed long-term durability evaluations of the installed geomembranes. The findings of the research and testing efforts performed by each of the aforementioned agencies are summarized below.

Hydro-Québec's Evaluation of Geomembrane Materials For Dams. In 1995, the Research Institute of Hydro-Québec published the results of their research to investigate all types of waterproofing liners, to ascertain properties and performance, to evaluate, and finally to recommend the most suitable materials for waterproofing of dams in cold climates (IREQ, 1998). This research was prompted by the fact that Hydro-Québec has many concrete gravity dams exposed to severe climatic conditions which entail frequent wetting-dehydrating and freeze-thaw cycles, and sometimes chemical attack and alkali-aggregate reaction (AAR). Consequently, many of their dams have experienced severe deterioration at the upstream face and are in need of repair. As a result, Hydro-Québec is considering installing long-lasting watertight synthetic liners on the upstream face of some of their aging dams which have seepage problems. The abridged version of the findings of Hydro-Québec's research was published in a 1998 report under the auspices of ICOLD (IREQ, 1998). The objectives and findings of Hydro-Québec provide a timely independent evaluation of geomembranes currently available on the market.

The experimental phase determined that the PVC geomembrane heat-coupled during extrusion to a nonwoven geotextile, and a polyurethane geomembrane were found to have the best properties, and were recommended for use as a protection system on the upstream face of dams.

Figure 2.27. CARPI liner system on dam in Alps.

The U.S. Army Corps of Engineers Evaluation of Geomembrane Facing Systems for Dams. Like Hydro-Québec, the U.S. Army Corps of Engineers (Corps) has many concrete dams located in harsh environments. Identifying and evaluating ways to repair and maintain deteriorating concrete dams has been a recent focus of the Corps' Repair, Evaluation, Maintenance Program (REMR).

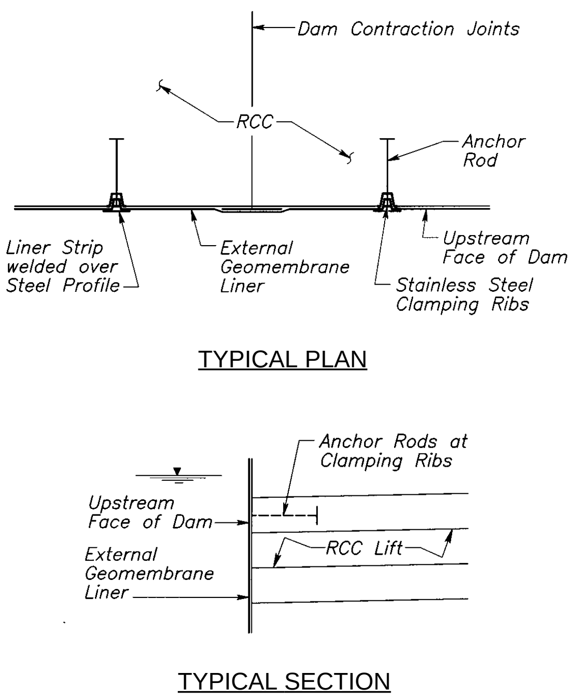
Since most geomembrane installations have involved dewatering the structure, which is often undesirable, the Corps set out to investigate a procedure to install geomembranes without dewatering (McDonald, 1998). Phase I of the study included research and material testing. Phase II was a demonstration of underwater installation of the system on a specially fabricated concrete structure. Of the materials tested, CARPI's PVC membrane backed with a nonwoven geotextile showed the best combined rupture resistance, conformability, and elastic recovery. The recommended underwater design consisted of a HDPE geonet drainage layer and CARPI's PVC geomembrane backed with a geotextile. The procedures were subsequently successfully demonstrated in 1997 on the first full-scale project, Lost Creek Dam, a concrete arch dam located in northern California. The success of this project resulted in the installation procedure being incorporated into the Corps' Engineering Manual 1110-2-2002 titled "Evaluation and Repair of Concrete Structures."

Figure 2.28. CARPI PVC liner system being installed on Lost Creek Dam, CA.

The Enté Nazionale Energia Elettrica (ENEL) of Italy Experience. ENEL of Italy has used the CARPI geomembrane system on nine of their aging concrete and masonry dams. Their first dam to use this system was Lago Baitone in 1970. The tallest ENEL dam where this system has been installed is Piano Barbellino Dam. Piano Barbellino Dam is 226 feet high and the geomembrane liner was installed in 1987. Beginning in 1995, ENEL began a research program to evaluate the long-term performance of the CARPI liners on their dams (Cazzuffi, 1995; Cazzuffi, 1998). The program involved collecting a variety of samples from six of their dams for various exposure conditions. The samples were tested for the following characteristics: plasticizer content, hardness, longitudinal and transverse tensile strain capacity, longitudinal and transverse tensile strength, permeability, and hardness. Review of the plots of the raw data from the six ENEL dams shows that the noted changes in the tested properties are very minor and that the liner material remained very stable with time.

CARPI has estimated that the service life of their PVC liner material is at least 50 years above water and 200 years below water. However, if the liner is permanently exposed and accessible, the liner may be susceptible to damage by vandalism. If damage were to occur due to vandalism, debris impact, or any other means, the liner can be repaired in the dry by simply heat welding a patch of the same material over the damaged area. Below water, repairs can be performed by patching using adhesives or by battening (McDonald, 1998).

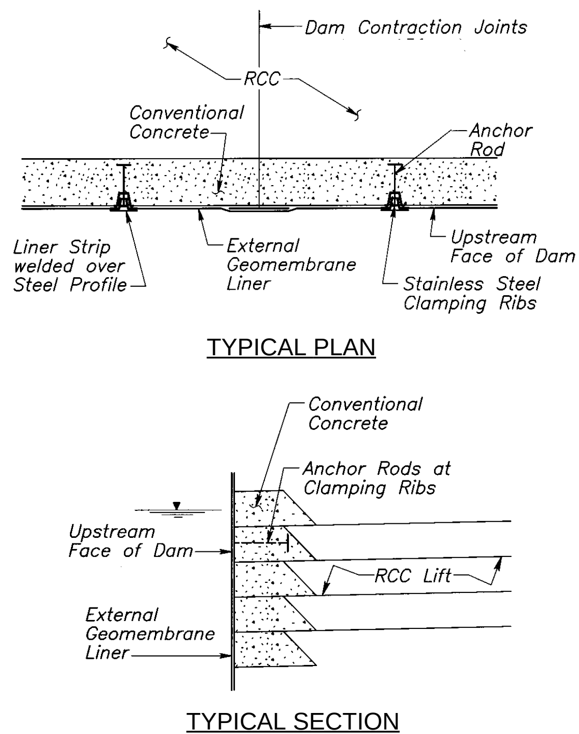
The CARPI system is the most popular and proven external geomembrane system. It consists of a 100-mil-thick high performance PVC geomembrane coupled with a geotextile fastened to the upstream face of the dam using a stainless steel clamping system referred to as “profiles.” The CARPI system is a proprietary system requiring installation by the manufacturer. The sheets of geomembrane material are attached vertically to the face of the dam with the steel profiles spaced approximately 13 feet apart. The sheets of membrane can normally cover the full height of the dam as one piece without horizontal joints. The vertical joints are sealed with heat-welded PVC strips.



Formed RCC with External Liner

Figure 2.29. Typical plan and section of formed RCC with external liner upstream facing system.

This system is termed a “drained system” as the geotextile attached to the downstream face of the geomembrane can be designed to act as a drain. For some applications an HDPE geonet, 4 mm thick with a diamond-shaped mesh, is installed behind the geocomposite to increase the drainage capacity of the system; however, the drainage net is optional. The steel profiles serve to tension the sheets snugly against the dam face as well as provide a conduit for any seepage or condensation. The metal profiles leave a gap between the geomembrane and the dam facing. Water is collected and conveyed through the profiles to a collection system installed at the heel of the dam. When a “drained system” is used, allowances can be made to the design of the dam to account for the reduction of internal hydrostatic pressure. The external geomembrane system can be installed at any time following completion of RCC placement. Installation is not significantly affected by climatic conditions.

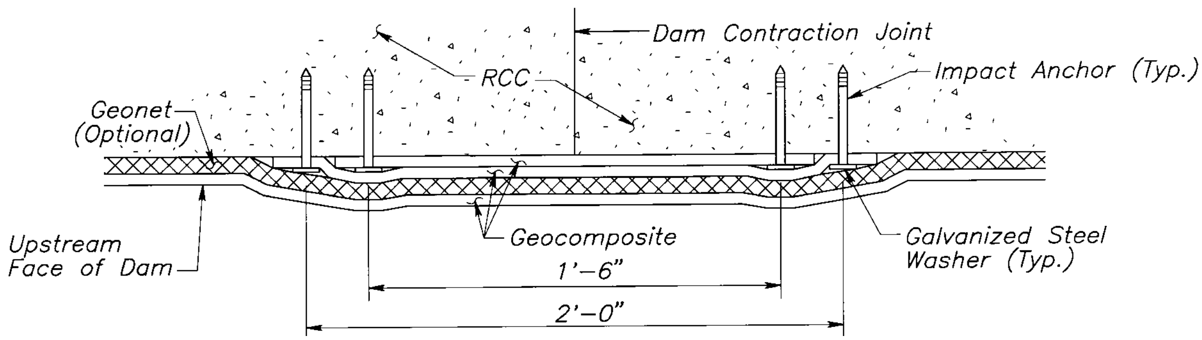


Formed Unreinforced Concrete with External Liner

Figure 2.30. Typical plan and section of formed conventional concrete placed concurrently with RCC, with external liner, upstream facing system.

Use of the CARPI external geomembrane system is much more popular outside of the United States and has been used for over 30 years on both small and large existing conventional concrete and new RCC dams. Approximately 39 dams outside the United States, mostly rehabilitation projects in Italy and France, have used this system. The dams range in height from 16 feet to 570 feet and are located in a range of different climates including extreme cold climates such as the Alps, and hot tropical climates such as Honduras.

Olivenhain Dam in San Diego, California will be the first RCC dam in the United States to use an exposed geomembrane system. Olivenhain Dam will be 306 feet high and is scheduled to be com-



Contraction Joint Detail

Figure 2.31. Typical CARPI contraction joint detail.

pleted in 2003. La Miel Dam in Columbia is currently under construction and when completed (2003) will be the tallest RCC dam in the world to use the CARPI facing system at a height of 617 feet.

Figure 2.32. CARPI liner system on Balambano Dam, Indonesia.

A potential refinement to a "drained system" includes the use of a "smart geotextile." The concept has its origins in damage and leak control systems which were developed beginning in the early 1990s to detect damage to geomembrane liners used for municipal and hazardous waste landfills, industrial wastes, lagoons, tanks, and similar facilities that use geomembranes. Damage to the geomembrane liner is detected by electric current. Special sensors are installed behind the geomembrane liner during construction. These sensors are connected by wire to a central control box or computer. The data acquired can be interpreted by customized software which produces plots or three dimensional graphics identifying actual damage positions. Should a leak in the liner develop, the sensor system would send electric signals to a control station which would provide information concerning the time and location of the leak.

CARPI has also developed and patented an external waterstop system for waterproofing RCC dam contraction joints and cracks. The external waterstop system, shown in Figures 2.33 and 2.34, consists of a series of geocomposite layers secured over the joint or crack. The geocomposite layers generally include a transition or anti-puncture membrane against the face of the dam, a central support membrane, and on the outside, a waterproofing membrane sealed against the upstream face of the dam. Flat metal profiles are anchor bolted to the dam at the sides to provide a watertight seal. CARPI's external waterstop system has been installed on four RCC dams with heights ranging from 165 to 400 feet.

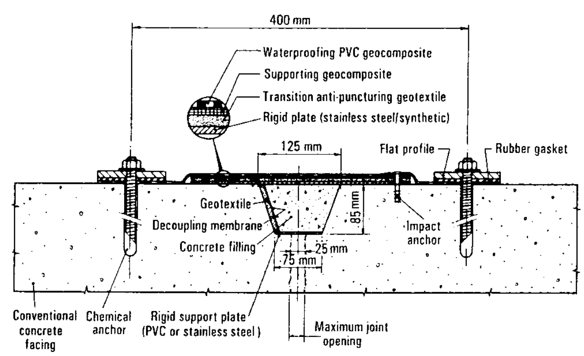


Figure 2.33. CARPI external waterstop System (drawing courtesy of CARPI).

Advantages of the this facing system include a proven record of performance on many dams, including several in the Alps, and extensive independent testing and evaluation, providing a high degree of confidence in its use. Disadvantages include the possibility of damage from vandalism, a service life of the liner material which may be less than the life of the project, a proprietary system, and lack of a long-term performance record for the smart geotextile installed in similar installations.

Figure 2.34. CARPI external waterstop system (photographs courtesy of CARPI).

2.2.9 Earth or Rock Fill Placed Concurrently With RCC. As the name implies, successive lifts of earth or rock fill are placed upstream of the RCC dam concurrently with each RCC lift. With this facing system either the lift of earth or rock fill can be placed before the lift of RCC, or the RCC can be placed first. RCC material quantity can be minimized by placing the RCC lift before the upstream lift of fill material by using a temporary 1-foot-high form supported by the previous lift of fill to create a vertical upstream RCC face. A zone of impervious earth fill can be placed at the upstream face to improve watertightness. The soil fill covering the upstream face of the RCC will protect the untreated RCC face from weathering and provide an insulating zone to reduce cracking from thermally-induced stresses. This facing system has primarily been used to construct small detention dams. (The North Loop detention dams and the Great Hills Dam in Texas, and Pajarito Dam in New Mexico are examples of dams using this facing method.) For these dams the upstream earth fill or rock fill embankment section of the dam supports most of the roadway while the narrow downstream RCC section provides embankment overtopping protection.

2.2.10 Internally Vibrated Grout-Enriched RCC. Grout-enriched RCC (GE-RCC) has been used extensively in China for upstream and downstream facing of RCC dams, for RCC placement against formwork and rock abutments, and at embedded items such as waterstops. This technology is currently under investigation in the United States and was evaluated as part of the design phase RCC trial placements for the Olivenhain Dam Project. Its development, current applications, and limitations are described in the following paragraphs.

GE-RCC was developed to enhance the workability and/or durability of RCC for use adjacent to formwork, around embedded items such as waterstops, adjacent to rock abutment surfaces, and at the upstream and downstream faces of RCC dams. The process of placing GE-RCC basically consists of altering the composition of RCC by adding a cement and water grout mixture to the RCC mixture. Theoretically, the grout is proportioned and distributed into the RCC to produce a mixture that

Figure 2.35. Earth fill placed concurrently with RCC at upstream face of Pajarito Dam, NM (photo courtesy of Terrence Arnold).

has characteristics similar to those of conventional non-air-entrained concrete. The typical construction process for placing GE-RCC includes the following steps: (1) place bedding mix consisting of a sand-cement mortar mix on previously compacted RCC lift surface, (2) place and spread RCC on top of bedding mix, (3) manually spread grout on top of uncompacted RCC lift surface, (4) consolidate GE-RCC with internal pneumatic vibrators, and (5) compact remainder of RCC lift. While this process sounds relatively straightforward, its successful use requires special attention to several details.

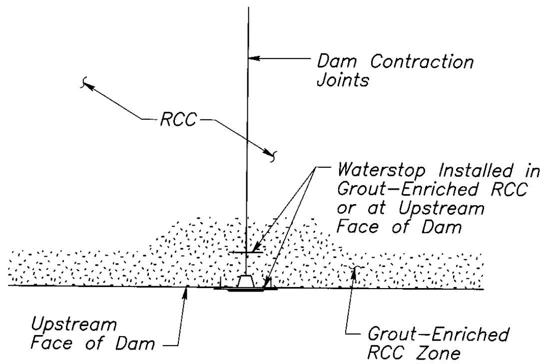
Use of Grout-Enriched RCC in China. The first use in China was in the Yantan cofferdam in 1987. It has also been used at several other dams including Jiangya Dam, a 420-foot-high RCC dam completed in 1999. At Jiangya a 3/8-inch to 3/4-inch layer of bedding mix was placed on the previous RCC lift surface prior to spreading the next lift of RCC. A 12-inch-thick layer of RCC was spread over the bedding mix, a thin layer of grout was spread over the RCC, and the RCC was internally vibrated with gang 6-inch pneumatic vibrators mounted on a tracked backhoe. The RCC contained approximately 326 pounds per cubic yard of cementitious material and had a Vebe time of about 10 seconds or less (Brian Forbes, Et Al., 1999), (William Moler, 1998). From all accounts, the Chinese appear to have had very good success with GE-RCC. However, some Chinese engineers report that GE-RCC used at the upstream or downstream faces of dams has experienced more cracking than expected.

Grout-Enriched Placing Trials in the United States. In 2000, interest in GE-RCC developed in the United States. Although earlier placing trials may have occurred, the most recent experiences with GE-RCC occurred at Atlanta Road Dam in Cobb County, Georgia and at Olivenhain Dam in San Diego County, California. The trials at Atlanta Road Dam, however, used plate tampers to externally vibrate the GE-RCC instead of using internal vibration to consolidate the concrete. The trials at Olivenhain Dam attempted to duplicate the approach developed in China.

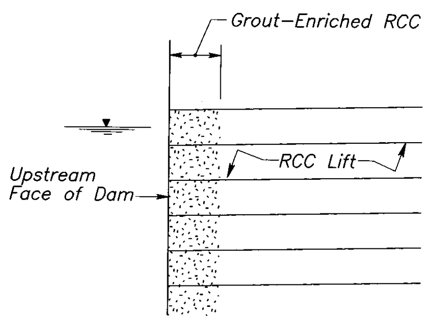
Experience at Olivenhain Dam Trial Placement. The RCC placing trials for the Olivenhain Dam included investigation of GE-RCC as a potential facing system and treatment at rock abutments for the project. The first step of the process was to select target mix proportions for the GE-RCC. The basic approach of the mix design process was to convert the RCC into a non-air-entrained "conventional concrete" with a slump of about 3 to 4 inches and a compressive strength of 3000 pounds per square inch. Using the standard practices in ACI 211, the GE-

Figure 2.36. Placement and internal vibration of grout-enriched RCC at Jiangya Dam in China (photo courtesy of William A. Moler).

RCC required a cementitious content of approximately 475 pounds per cubic yard (ppcy), and a water content of 285 ppcy. Since the RCC mix proportions were pre-established, the grout proportions and the ratio of grout to RCC were the remaining variables to obtain the desired GE-RCC mix.



TYPICAL PLAN



TYPICAL SECTION

Grout-Enriched RCC Against Formwork

Figure 2.37. Typical plan and section of grout-enriched RCC against formwork upstream facing system.

Several techniques were tried for placing and consolidating the GE-RCC. The first technique was to spread the RCC, then backblade a 1½-inch-deep by 3-foot-wide trench along the formwork. The grout was then poured to fill the trench and vibrated with a 2½-inch-diameter Micon high-cycle electric vibrator operating at 10,800 vibrations per minute. For the first trial, most of the grout remained on the surface and did not penetrate or blend with the RCC.

A second trial was performed using the Micon high-cycle electric vibrator. For the second trial, only a small portion of grout was placed on top of the RCC, thus allowing better observation of the response of the RCC to the internal vibration. Additional water was added to the RCC mix, lowering the Vebe time from 25 seconds to about 15 seconds. Based on observation of the second trial, it was apparent that the high-cycle vibrator was not consolidating the RCC, nor blending the grout into the mix. The vibrator also left open holes where it had been inserted into the RCC

Two additional trials were performed using the GE-RCC as a facing system. For these trials, two 3-inch-diameter Malon pneumatic vibrators were used. The vibrators were gang mounted 12 inches apart on a backhoe. The pneumatic vibrators did “hit” considerably harder than the high-cycle vibrator due to higher amplitudes, and they did consolidate the RCC within a few inches of the vibrators. However, the vibrators still left holes upon extraction, the consolidation did not appear to be complete, and the consolidation was very localized around the vibrators.

Based on the results of internal vibration for the facing system trials, it was decided to eliminate trials of GE-RCC as an abutment treatment for the Olivenhain Dam. It was concluded that since the RCC design mix had a 15 to 20 second Vebe time and considerably less cementitious content compared to RCC mixes used by others for GE-RCC, it was too dry to be successfully consolidated by internal vibration, and thus would not allow for penetration and proper blending of the grout. It was concluded that for GE-RCC to work, the RCC mix has to be sufficiently workable so that it alone can be consolidated by internal vibration, thus allowing for penetration and blending of the grout.

The U.S. Army Corps has undertaken a research program on GE-RCC to study among other things, construction techniques, air entrainment of GE-RCC, and optimum RCC mix proportions to facilitate GE-RCC.

2.3. Other Upstream Facing Systems

2.3.1 Composite Facing Systems. The best features of two or more upstream facing systems can be realized by selectively using them within different zones of the dam. For example, a reinforced concrete facing system or precast panel facing system can be installed near the top of the dam to cover and protect the normal exposed area of the dam, and an exposed geomembrane liner could be installed below this zone. Advantages of selective use of two or more systems may include: (1) the exposed face of the dam would be protected from vandalism, (2) the service life of the liner under water would be similar to the service life of the project, and (3) the lined portion of the dam would benefit from the

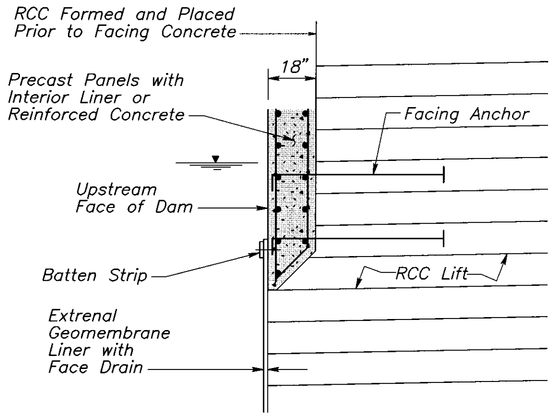


Figure 2.38. Transition detail from an exposed liner facing system to a concrete facing system.

unique features only provided by an exterior liner facing system. A detail illustrating a potential transition from an exposed liner system to a concrete facing system is presented in Figure 2.38.

The 38-foot high North Tyger River Dam in South Carolina used a combination of precast panels with the "T-Lock" liner system and formed RCC. Where the upstream face had water directly against it, the panels were used. In the areas where soil was backfilled against the face, the face was formed vertically with RCC. The backfill soil was a select clayey type that served as a waterproofing system for that portion of the upstream face.

Figure 2.39. Construction of upstream face of Barnard Creek Dam, UT.

2.3.2 Shotcrete Facing. Barnard Creek Dam in Utah is a 59-foot-high debris/flood control structure where the RCC was placed in only four 24-hour days. Because of its narrow width, the forming of the upstream face of the dam was on the critical path in the overall RCC placement schedule. The contractor proposed to use a combination of Tensar Strips, two-sided wire baskets, and a geotextile to "form" a vertical upstream face. Figure 2.39 shows the installation process. Each installation of the wire baskets would allow for two lifts of RCC to be placed. Upon completion of the dam, the exposed geotextile and Tensar strips were removed and a 6-inch layer of shotcrete was applied over the entire upstream face of the dam.

2.3.3 Unformed Sloping RCC Face. For low height applications it may be cost effective to forgo a vertical formed face and place the RCC on a 1:1 slope. This was the design for Grace Lake Dam in Alabama in 1991. This 35-foot-high dam was constructed in 48 hours with both the upstream and downstream slopes placed at 1:1.

2.4 Summary of Upstream Facing Systems

A review of the nine basic facing systems described above and the frequency of their use on new RCC dams constructed in the United States, as presented in Table 1.2, shows that formed unreinforced conventional concrete and precast panels with an internal liner are the most popular facing systems. However, a variety of other facing systems have also been effectively used. Each facing system has its advantages and disadvantages. It should be recognized that an upstream facing system that is suitable for one dam may not be adequate or appropriate for other dams. Selection of the facing system must consider the intended purpose of the facility, local climatic conditions, materials availability, dam size, service life, and owner preferences. The primary criteria for selecting an upstream facing system should therefore include the following five factors: (1) cost, (2) appearance, (3) watertightness, (4) durability, and (5) constructibility. Preliminary screening of the various facing options can be performed by assigning a point rating to each factor. The applicability of each factor is then weighed against its overall importance for the specific project in question and the total points for each factor are summed to obtain a final score. When comparing facing systems, care must be exercised to compare systems on an equal basis, noting that some facing systems can include features such as drainage that may offset other project features such as the need for drilled drain holes in the body of the dam, the need for bedding mix, and the RCC mix design.

Table 2.1 is presented as a general guide to help select one of the nine upstream facing systems discussed in this guide manual. The evaluations for each factor are based on the performance of the facing system at existing dams and the authors' experience and judgment. Note that these represent a general evaluation and could vary considerably depending on local climatic conditions, equipment availability, dam layout, quality of workmanship, and many other factors.

Table 2.1. Design Factor Ratings for Upstream Facing Systems

Upstream Facing System	Cost $/Ft² - 2000(1)	Appearance	Water-tightness	Durability	Construct-ibility
1. Formed/Exposed RCC	Low $4-$8	Poor-Fair	Poor	Poor-Fair	Routine
2. Earth or Rock Fill Placed Concurrently with RCC	Low	Good	Depends on Fill	Good	Routine
3. RCC Against Precast Panels Without A Liner	Moderate $8-$16	Good	Poor	Good	Routine
4. RCC Against Slip-formed Facing Elements	Moderate $6-$10	Fair-Good	Poor-Good	Good	Moderate-Difficult
5. Formed Conventional Unreinforced Concrete	Moderate $5-$19	Fair	Good	Good	Moderate
7. RCC Against Precast Panels With Liner	Low-Moderate $10-$20	Good	Good	Good	Routine-Moderate
8. Exposed Liner 0n Formed RCC	High $18-$30	Good	Good	Fair	Proprietary
9. Reinforced Concrete Placed After RCC	High $20-$35	Good	Good	Good	Difficult

[i] Costs are approximate and in year 2000 US dollars. Actual costs can vary depending on location, site conditions, and many other factors.

CHAPTER 3

Downstream Facing Systems For RCC Dams and RCC Spillways

3.1 General

Whereas the selection of an upstream facing system is often centered on the issue of seepage control, the selection of the downstream facing system is primarily concerned with durability, constructibility, aesthetics, and sometimes energy dissipation for overtopping flows. Here again, the designer must consider the intended purpose of the facility, local climatic conditions, materials availability, dam size and shape, safety, owner preferences, and cost.

3.2 Stepped Versus Smooth/Sloping Downstream Face

Stepped spillways have been in use on dams for more than 3,000 years (Chanson, 2000). The use of stepped spillways from ancient times to the early 20th century appears to result from a natural outgrowth in the use of stone masonry for dam construction. However, the energy dissipating characteristics of early stepped spillway designs do not appear to have been investigated in detail. Likewise, primarily because of the recent trend in the use of RCC technology and the easy adaptation to stepped configurations this technology affords, stepped spillways are experiencing renewed attention.

In general, the steps act as roughness elements that reduce the terminal flow velocity and provide significant energy dissipation. Recent model studies by the USDA Agricultural Research Service, the Bureau of Reclamation, and others were performed to evaluate the flow transition from the level spillway crest to the sloping steps, the energy dissipation of the steps, and stilling basing performance. These physical model studies show that the energy dissipation provided by the steps can allow significant reduction in the size of the stilling basin as compared to a conventional chute spillway (Chanson, 1997), (Rice, 1996), (Chamani, 1994), (Christodoulou, 1993), and (McLean, 1993).

Figure 3.1. Unformed RCC stepped spillway, Ringtown Dam No. 5, PA.

Figure 3.2. Formed conventional unreinforced concrete spillway steps, Monksville Dam, NJ.

From the current body of research on stepped spillways, there appears to be a general agreement on a number of issues, including the presence of nappe and skimming flows, and the significance of air entrainment on stepped chutes. Although progress has been achieved, more research is needed to gain a sound understanding of the complex flow patterns. Experimental studies suggest that cavitation is not an issue on stepped spillways because the flow velocities remain low. Step damage caused by pressure fluctuations in the step cavities, however, may be a problem. A book titled *"Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways"* by Dr. H. Chanson, published in 1995, presents a comprehensive treatment of stepped spillways. Most designers continue to rely on intuition and, when possible, small scale physical models to design stepped spillways.

3.3 Criteria for Evaluating Downstream Facing Systems

3.3.1 General. The general criteria for evaluating the downstream facing system for most RCC dams includes the following five evaluation factors:

1. Appearance
2. Constructibility
3. Durability
4. Cost
5. Public Accessibility and Safety

These factors are generally the same as those used to evaluate upstream facing systems except that seepage control at the downstream face is primarily concerned with collection, transmission, and monitoring seepage rather than watertightness. In some cases, seepage emerging from the downstream face of the dam may be acceptable from a structural stability perspective, but may not be acceptable for public perception and aesthetic reasons. An additional evaluation criterion not considered in the evaluation of upstream facing systems is public accessibility and safety which is discussed below. Additional concerns regarding appearance that are unique to the downstream face of RCC dams are also discussed herein. For a discussion of the other four evaluation criteria refer to Paragraph 2.1 – *Criteria for Evaluating Upstream Facing Systems.* A general assessment of the overall rating of each downstream facing system for each of the evaluation factors is presented at the end of this section.

Figure 3.3. Downstream stepped face of Bullard Creek Dam (photo courtesy of Benjamin Doerge).

3.3.2 Public Accessibility and Safety. Depending upon the location and site conditions for a given dam, public accessibility to the downstream face, especially if the face is moderately sloped or stair-stepped, can pose a serious concern for public safety and the potential for vandalism. Public accessibility to the downstream face of the dam determines the degree of concern for the designer regarding this issue. For certain instances, other natural or man-made barriers, such as fencing, may negate or minimize the relevance of this issue. Situations could occur where a person(s) could view climbing the downstream face as a challenge and may attempt to scale the face.

Any of the available downstream facing systems can be constructed with either a sloping or a stepped surface. Some RCC dams, like Bullard Creek Dam, were designed and constructed with a stepped face where steps with different heights and widths were used (see Figure 3.3). For any dam, a stepped surface, as opposed to a sloping surface, increases the potential danger of a fall injury by improving access to the face. However, depending upon the grade, even a sloping surface presents a similar danger. Minimizing public access to the downstream face must be weighed against providing access for future inspection and maintenance.

3.3.3 Appearance. The downstream face of any dam is typically the most noticeable feature of the entire project. This is especially true for large RCC dams. With regard to the public eye, the history of dams, including RCC dams, has demonstrated that the need to provide a structure with a sound structural appearance is often very important. In the past, less-than-perfect concrete finishes and water leakage at the downstream face of a dam has caused the public to react with alarm. This reaction can arise when the public compares the appearance of the concrete finish on the downstream dam face to more familiar concrete structures. For an RCC dam using unformed or formed RCC on the downstream face, the raveled and / or irregular surface can cause a false perception of poor quality workmanship, which can place the structural integrity of the entire project in question. Even though the public's alarm is unwarranted, once initiated it is very difficult to dispel. Therefore, not only the aesthetics, but also the dam's appearance in terms of structural integrity, can be important features to be considered during design.

Figure 3.4. Seepage from downstream face, Willow Creek Dam, OR.

3.4 Downstream Facing Systems for RCC Dams and RCC Spillways

3.4.1 General. Twelve different downstream facing systems have been constructed on RCC dams (Dunstan, 2000). Some of the downstream facing systems are combinations of facing systems, particularly where the downstream face extends above and below surface grade. Several of the downstream facing systems used are unique to a particular dam site and are generally not available or possible at most other dam sites. The twelve downstream facing systems used worldwide are summarized in Table 1.1. Approximately 44 percent of the RCC dams constructed worldwide have a stepped chute face and 36 percent of the RCC spillways have a stepped downstream face. In the United States, approximately 37 percent of the RCC dams have a stepped downstream face, and approximately 50 percent of the RCC spillways have a stepped chute. Whether sloped or stepped, the slope of the downstream face for RCC dams constructed to date ranges between 0.5:1 (Horizontal:Vertical) to 1:1 (H:V) with the majority having a slope of 0.80:1 (H:V).

Although twelve different downstream facing systems have been used worldwide, for discussion, these systems can be categorized into nine basic systems. Variations within each type of facing system are discussed along with their advantages and disadvantages.

3.4.2 Unformed RCC. An unformed RCC face can be constructed on RCC dams where the downstream slope of the dam is generally flatter than 0.8 H : 1.0 V. For constructibility, a slope of at least 0.85 H : 1.0 V is sometimes preferred. Steeper slopes require downstream forms to maintain the slope as the natural angle of repose of the RCC mix is exceeded. The angle of repose of RCC mix mainly depends on the shape and grading of the aggregates, and mix workability.

When using an unformed RCC face, the face is normally overbuilt 1 to 2 feet to insure the design neat line is never compromised and to account for long- term loss of RCC due to raveling or weathering. This allowance accounts for the fact that it is difficult to achieve a high degree of compaction on the exposed RCC slope, resulting in lower density

Figure 3.5. Unformed RCC face, Monksville Dam, NJ.

and lower strength material at the face. As weathering progresses and the weaker, less dense RCC ravels, the stronger, more dense RCC is exposed at the surface. Attempts to compact the exposed slope have included motorized hand compactors, running the wheels of heavy equipment along the outer edge, and using specially designed compaction equipment mounted on hydraulic tractors. To minimize raveling, the contractor is often required to "trim" the loose RCC from the slope. A heavy chain or dozer track can be dragged up and down the slope to remove most of the uncompacted RCC.

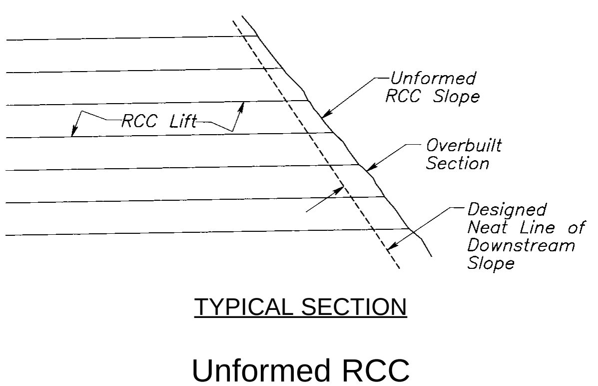


Figure 3.6. Typical section of unformed RCC downstream facing system.

A common occurrence for RCC dams which have been constructed with an unformed downstream face is the emergence of vegetation on the face after several years. The vegetation can be especially prolific and dense where the face is kept wet from seepage. Vegetation can be observed on the downstream faces of Willow Creek Dam and Galesville Dam in Oregon and Monksville Dam in New Jersey. Public and owner perception of the dam must also be considered when using this facing system. Even though the dam is designed to accept loss of some RCC material at the downstream face through weathering, the public's and/or owner's perception of the rough and irregular concrete surface may draw undo criticism and alarm.

Figure 3.7. Unformed RCC face with vegetation, Willow Creek Dam, OR.

Advantages of this facing system include uncomplicated RCC placement and low cost. Disadvantages include a rough unfinished appearance, poor durability in harsh climates if low-paste RCC mixes or low quality aggregates are used, and vegetative growth on the face that can increase maintenance costs and accelerate surface deterioration. Approximately 45 percent of the dams constructed in the United States use this facing system on the non-overflow section of the dam and about 9 percent of the RCC spillways have this facing system. The tallest dam in the world constructed with this facing system is Trigomil Dam in Mexico at a height of 328 feet.

3.4.3 Formed RCC. This downstream facing system is simply constructed by forming the RCC face with conventional removable forms. Using formwork to construct the downstream face of an RCC dam has primarily been used where the downstream slope is steeper than 0.8 H : 1.0 V, and/or where a stepped surface is desired for energy dissipation of overtopping flows or for aesthetics. Due to the method of construction, a formed RCC face is limited to a stepped configuration. Forming the RCC provides a finished surface that has fewer irregularities than unformed RCC. However, variations in the finished appearance of the RCC steps will occur. Isolated honeycombing and rock pockets will occur, and lift lines will likely be visible.

To improve the density and surface appearance at the formed RCC face, a fillet of bedding mix can be placed against the base of the form prior to plac-

Figure 3.8. Examples of formed RCC steps of poor, fair, and good quality (left to right).

Figure 3.9. Formed RCC face, Long Run Dam, PA.

ing the next RCC lift. The fillet of bedding mortar serves to fill any voids which can commonly occur at the bottom of RCC lifts placed against formwork due to inability to achieve sufficient compaction. If the RCC is then carefully compacted, the texture of the finished face can approach that of conventional concrete. Examples of dams which have used this downstream facing system include: Long Run Dam in Pennsylvania, and Hudson River #11 Dam and Big Haynes Dam, both in Georgia. Formed RCC steps are currently planned for Olivenhain Dam in California.

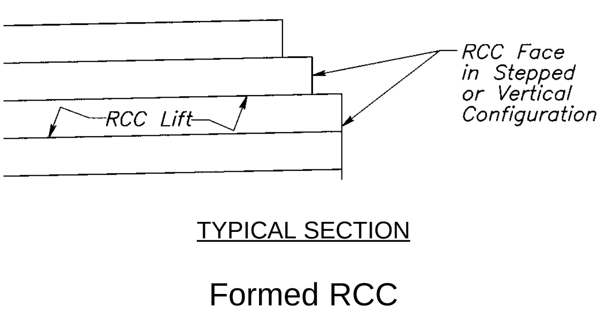


Figure 3.10. Typical section of formed RCC downstream facing system

Figure 3.11. RCC slip-formed face, Woody Branch Dam, TX.

A paving machine was used to place the majority of the RCC at Woody Branch Dam in Texas. The paving machine has an attachment which formed 9-inch-high RCC steps as seen in Figure 3.11 and Figure 3.12.

Figure 3.12. Paving machine and attachment used to form 9-inch-high steps at Woody Branch Dam, TX.

Advantages of this facing system include low cost and no additional installation time required after RCC placement. Disadvantages include the installation and removal of formwork, the generally rough unfinished appearance, and, in harsh climates, the potential for poor durability if low-paste RCC mixes or low-quality aggregates are used. This facing system is normally selected for dams where severe weathering or aesthetics are not a primary concern.

3.4.4 Formed Conventional Concrete Placed Concurrently with RCC. This facing system is the most popular downstream facing system for both non-overflow and overflow sections. It is very similar to the formed RCC facing system except that a 1- to 3-foot-wide strip of unreinforced conventional concrete is placed against the downstream form prior to or following placing and compacting the RCC. If the facing is placed first, the RCC is spread and compacted into the conventional concrete. The minimum compressive strength of the conventional concrete is 3,000 psi and the concrete should be air entrained. Generally, a retarder is added to extend the set time of the concrete.

Figure 3.13. Formed conventional concrete face, New Elmer Thomas Dam, OK.

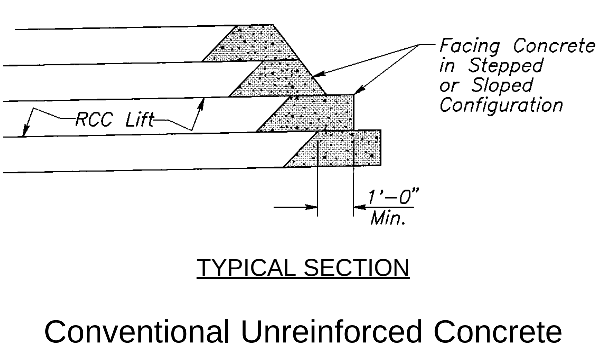


Figure 3.14. Typical section of formed unreinforced concrete downstream facing system.

Advantages of this facing system include readily available construction materials, no additional installation time after RCC placement, and a durable and attractive exposed face if attention is paid to setting forms and consolidating the conventional concrete. This facing system is often used to provide an inexpensive protective layer for RCC dams located in moderate to severe climates. Disadvantages include the need to coordinate multiple construction materials and activities that are time-critical. The production and delivery of the conventional concrete must be placed within a limited time frame (30-45 minutes) concurrent with RCC placement. In addition, conventional concrete placement equipment further congests the lift surface, and the exposed face of the conventional concrete is prone to cracking because of differences in elastic and shrinkage properties from those of the RCC. Consolidation at the conventional concrete and RCC interface can also be difficult to achieve.

Figure 3.15. Formed conventional concrete face of New Elmer Thomas Dam, OK.

Middle Fork Dam and Stagecoach Dam in Colorado, and New Elmer Thomas Dam in Oklahoma are examples of dams which have used this method. Over 50 percent of the RCC dams worldwide and in the United States were constructed with this facing system.

3.4.5 RCC Against Precast Concrete Panels. This facing system consists of precast concrete panels with typical heights of 2-6 feet, lengths of 8-16 feet, and thicknesses of 4-6 inches. This system uses the pre-cast concrete panel as a stay-in-place form for RCC placement. As RCC placement progresses, lower panels with anchor bars that are embedded in the lower lifts of RCC provide support for the panels at the placement level through the use of a temporary bracing system commonly referred to as "strongbacks." One important advantage to the integral process of this system is that when RCC placement is complete, construction of the facing system is also complete.

Figure 3.16. RCC against precast concrete panels.

Due to the economy in using a thin panel with a comparatively larger height and width dimension, it is best-suited for applications where a vertical facing is desired. It is commonly used in the chimney section of RCC gravity dams to form the vertical downstream face. The most economical use of this system is when a similar system is also used for the upstream face of the dam. Every RCC dam that used precast panels on the upstream face of the dam also used precast panels on the downstream face of the chimney section.

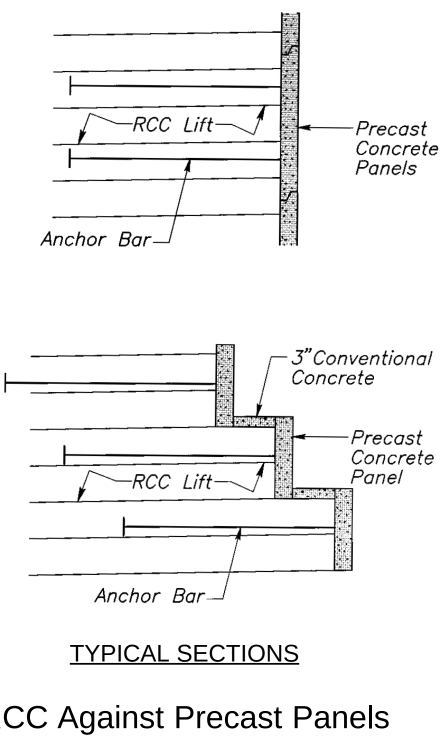


Figure 3.17. Typical sections of RCC against precast panels downstream facing system.

Precast panels with heights equal to 1 or 2 RCC lift heights (1-2 feet) could possibly be used to construct the sloping or stepped portion of the downstream face. However, a sloping or stepped face does not as easily accommodate a temporary bracing system as would a vertical face. Inadequately braced panels have a tendency to displace during RCC placement, causing further panel and bracing alignment difficulties with successive lifts. A self-supporting configuration such as an “L” or inverted “T” shaped panel could possibly be used to help combat this difficulty.

Figure 3.18. Precast panels used to construct steps at Tongue River Dam, MT.

Precast concrete panels were used at the overtopping spillway project at Tongue River Dam in Montana (see Figures 3.18 and 3.19). The 2 foot 10 inch tall panels were used to form the vertical faces of the 22 steps of the spillway. The panels served as forms for the RCC and were left in place as the exposed wearing surface of the spillway. RCC was placed to within 6-8 inches of the tops of the panels and then conventional concrete was placed over the

Figure 3.19. Completed RCC stepped spillway at Tongue River Dam, MT.

RCC to the tops of the panels. By completely encapsulating the RCC with panels and conventional concrete, a lean RCC mix could be used for the spillway mass. Because of the severe weather in that region, if the RCC was not protected, a rich RCC mix would have been required to provide the necessary durability.

Due to their comparatively thin cross section, panels are more susceptible than other available sections to hairline cracking at their surface and spalling along their edges during handling and RCC placement. However, the problem can be overcome with adequate attention to design and construction details.

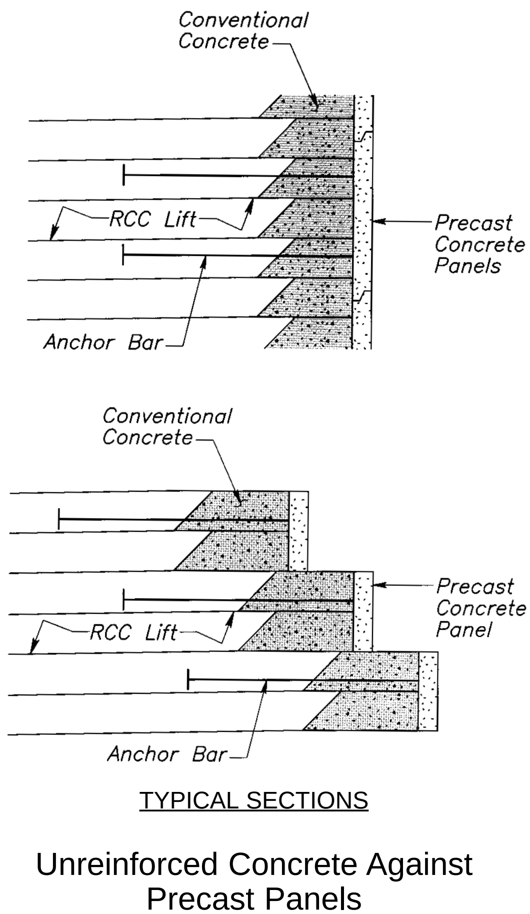


Figure 3.20. Typical sections of unreinforced concrete against precast panels downstream facing system.

Precast concrete elements were first used to form the downstream face of an RCC dam in 1984 to construct the downstream face of the North Loop Detention Dams in Texas. Aesthetics were important for the dams, which were part of a business park development. In addition to forming the downstream face of the dams, the precast concrete panels were used to form a three-level continuous planter across the dams as shown in Figure 3.21 (Hansen, 1991).

Figure 3.21. Downstream face of North Loop Detention Dam, TX.

Advantages of this facing system include no additional installation required after RCC placement, a durable and attractive exposed face, and potential use of color pigmentation additives as an aesthetic treatment. Disadvantages include higher cost.

3.4.6 RCC Against Precast Concrete Blocks. This type of facing system consists of precast concrete blocks with heights of 1 to 2 feet and lengths of 8 to 24 feet. This system is very similar to the precast concrete panel system because the blocks also serve as a stay-in-place form during RCC placement. This system also involves an integral process, which means that when RCC placement is complete, the construction of the downstream facing system is also complete.

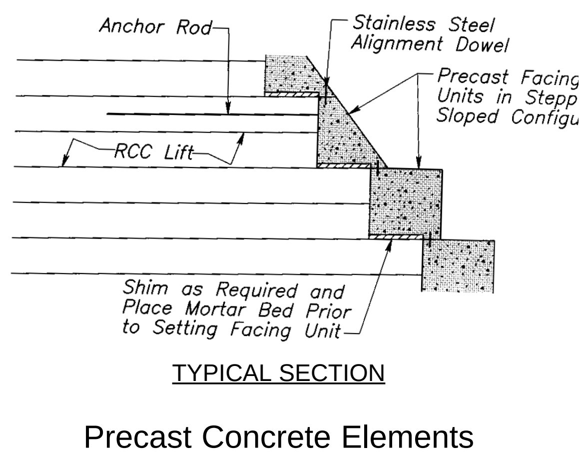


Figure 3.22. Typical section of precast concrete elements/blocks downstream facing system.

The stepped downstream slope of the spillway at Big Haynes Dam in Georgia was constructed using large rectangular precast concrete blocks. At North Fork Hughes River Dam in West Virginia, the exposed portion of the 0.6 H : 1.0 V downstream slope of the dam above the toe berm will be constructed using precast facing blocks with a sloped face. Each element will be centered on alignment dowels placed in the element below, and shimmed onto a bed of mortar. Each precast unit will be tied to the RCC dam with anchor rods which are threaded into an insert cast in the unit and embedded in a lift of RCC. A similar system was also used at Big Haynes Dam in Georgia.

Figure 3.23. Precast concrete blocks used to construct face of spillway at Big Haynes Dam, GA.

An important difference between pre-cast panels and blocks is that the blocks typically have a square, trapezoidal, or "L" shaped cross section making them free-standing or self-supporting, thus eliminating or minimizing the need for temporary bracing. Since the blocks overlap one another, they can be designed with internal connection pins, which assist with bracing during construction. Steel dowels have been used to interlock elements to prevent displacement during RCC placement. Steel rods are threaded into inserts at the inside face of each element. The rods extend into the RCC placement area and serve as additional means of anchorage for the system. Due to RCC's inherent uneven surface, bedding mortar is used at the contact of the block with the previously placed RCC lift to serve as a leveling mortar. Neoprene gaskets or expansion joint filler can be used where the block contacts the previously placed block to accommodate shrinkage of the mass RCC, which is especially important for high dams. The block section also provides better security against hairline cracking and spalling during handling and RCC placement.

Advantages of this facing system include the elimination of the need for external temporary bracing, no additional installation time required after RCC placement, a durable and attractive exposed surface, and potential use of color pigmentation additives for an aesthetic treatment. Disadvantages include higher cost due to the higher precast concrete volume and difficulty with setting and leveling blocks in fresh RCC and in achieving adequate alignment during installation, and heavy lifting requirements with a long reach for high dams. The tallest dam in the world constructed with this downstream facing system is Capanda Dam in Angola at a height of 361 feet.

Figure 3.24. Precast concrete block spillway face, Big Haynes Dam, GA.

3.4.7 Reinforced Concrete Cast After RCC Placement. This type of system is constructed by placing a reinforced concrete slab against the RCC after placement and offers the most durable and finished surface of the facing systems discussed herein. It is also the most expensive facing system. The slab is typically 1-2 feet thick, depending upon the structural requirements for the system. The details for this system are similar to concrete facing for rockfill dams.

Conventional reinforced concrete placed after RCC completion has been used to construct dams with smooth sloped faces and stair-stepped faces. At Siegrist Dam in Pennsylvania, the 0.8 H : 1.0 V smooth downstream face of the dam was first constructed by placing the RCC to the approximate template of the slope. Anchor bars were placed for a length of 8 feet into the lifts of RCC at the downstream slope before compaction. Final trimming and cleanup of the RCC slope was performed after all RCC was placed. Placement of the reinforced conventional concrete followed using both slipforming and conventional methods. Strip drains and waterstops were installed into the facing to intercept and eliminate any seepage from emerging at the downstream face.

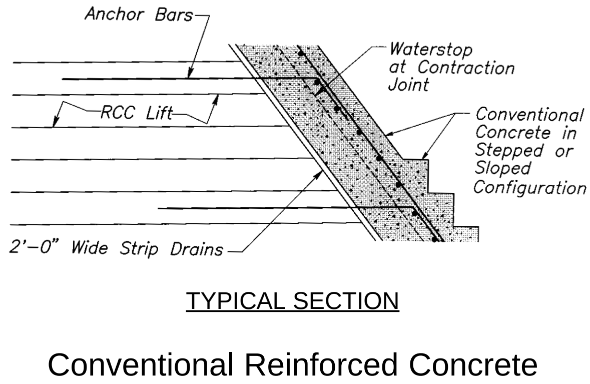


Figure 3.25. Typical section of reinforced concrete downstream facing system.

Since the RCC is typically placed unformed for this type of system, removal of the uncompacted layer of RCC at the exposed face must be performed prior to conventional concrete placement to provide adequate anchorage and to prevent fouling of drainage strips between the RCC and conventional concrete facing. Construction of this facing system must be performed after construction of the RCC due to the hazards and difficulties of working below RCC placement operations. This system is best-suited for dams in narrow canyons with large principal spillway widths where surface area is minimized and where the facing also serves the more primary purpose of forming the spillway chute.

Figure 3.26. Reinforced concrete facing placed after RCC, Siegrist Dam, PA.

Advantages of this system include its attractive and durable finish. Disadvantages include the highest cost of all facing systems and long installation time after RCC placement. The tallest dam in the world constructed with this facing system is Christian E. Siegrist Dam in the United States at a height of 130 feet.

3.4.8. RCC Against Slip-formed/Extruded Concrete Facing Elements. This cast-in-place downstream facing system can be constructed using a laser guided slip-form curbing machine. This facing system was primarily intended as a forming method and means of protecting the RCC from severe weather environments, but may also be used to form steps for energy dissipation.

On Upper Stillwater Dam, the 2-foot high interlocking curbs were constructed of 0.5-inch-slump conventional concrete in continuous lengths from 500 feet at the base to 2,673 feet at the crest. Each curb element required 4 hours to set before RCC could be placed against the element. The geometry of the facing elements was different from the dam to the overflow section. The facing elements for the dam created a smooth sloping downstream face, while the facing elements for the overflow section created steps with a 2-foot rise and 1-foot ± run. The finished downstream slopes of the dam were 0.6 H : 1.0 V and 0.32 H : 1.0 V. Challenges encountered with this system included grade control, excessive slumping of the placed elements, and some delays in RCC placement while the placed elements were curing. A total of 98 miles of slip-formed elements were placed requiring a total of 87,000 cubic yards of concrete. Horizontal and vertical tolerances of 1½-inch were maintained during construction. No contraction joints were formed in the RCC or slip-formed elements during construction.

Figure 3.27. Slip-formed downstream face, Elk Creek Dam, OR.

Advantages of this system include a durable finish with no installation time required after RCC placement. Disadvantages include cracking because of differences in elastic and shrinkage properties from those of RCC, difficulty installing contraction joints, and additional equipment on the lift surface. It is also noted that this system has a higher unit

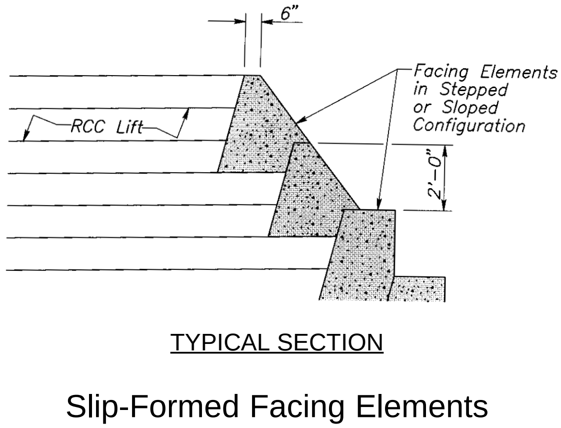


Figure 3.28. Typical section of slip-formed/extruded concrete downstream facing system.

cost for increasingly flatter downstream slopes due to the higher volume of conventional concrete needed for the slip-form element. For small dams with short crest lengths, this system is not practical since construction of the facing elements will impede RCC construction. The tallest RCC dam in the world to use this downstream facing system is Porce II Dam in Columbia at a height of 403 feet.

3.4.9. RCC Placed Concurrently with Fill. This facing method has been used when the downstream face of the RCC dam was steeper than 0.8 H : 1.0 V and in unique cases where fill material was readily available. Where seepage through the RCC is anticipated, a drainage system consisting of a layer of drainage material between the RCC and downstream earth or rock fill should be considered. RCC waste material or overbuild can be minimized by placing the downstream end of the RCC lift against a temporary 1-foot-high form before placing the earth or rock fill.

Figure 3.29. RCC placed concurrently with earth fill, Penn Forest Dam, PA.

This downstream facing system was used to construct the 180-foot-high, 0.5 H : 1.0 V downstream slope of Penn Forest Dam in Pennsylvania. The earth and rock fill placed at the downstream face was taken from the existing embankment dam at this site and was used to buttress the new RCC dam. In addition to providing a form for the RCC, the fill covering the downstream face of the RCC protects the untreated RCC face from weathering, provides an insulating zone to reduce cracking from thermally induced stresses, and increases the sliding and overturning stability of the dam.

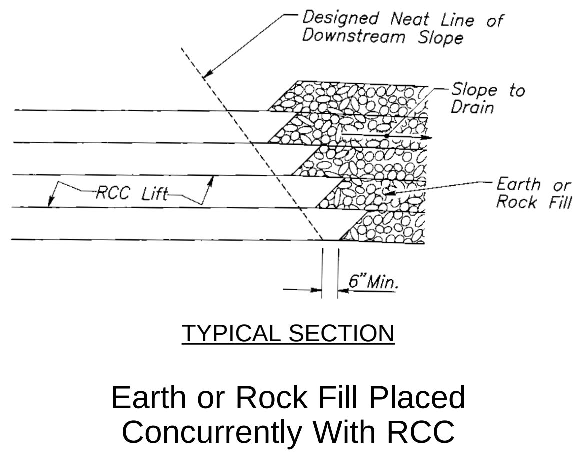


Figure 3.30. Typical section of earth or rock fill placed concurrently with RCC downstream facing system.

3.4.10 Mechanically Compacted Unformed RCC. This downstream facing system, which was popularized by French dam engineers, is constructed by mechanically compacting the unformed face of the RCC. It is generally selected for dams and spillways where aesthetics are not the primary concern. This method has been used for slopes of 0.75 horizontal to 1.0 vertical or flatter. The face is normally overbuilt 1 to 2 feet to allow for some deterioration due to low densities and to account for some compression of the material during compaction. Methods to mechanically compact the unformed face have included using motorized hand compactors, running the wheels of heavy equipment along the outer edge, and using specially designed compaction equipment mounted on hydraulic tractors as illustrated in Figures 3.31 and 3.32. The tallest RCC dam in the world constructed with this facing system is Petit Saut Dam in French Guyana at a height of 157 feet.

Figure 3.31. Mechanically compacted unformed RCC.

Figure 3.32. Mechanically compacted unformed RCC (photo by Barnard Construction).

3.5 Summary of Downstream Facing Systems for RCC Dams and Spillways

Like upstream facing systems, it is recognized that a downstream facing system that is suitable for one dam may not be suitable for another dam. Table 3.1 is presented as a general guide to help select one of the nine downstream facing systems presented in this guide manual. The evaluations for each factor presented in Table 3.1 are based on the performance of the facing system at existing dams and the authors' experience and judgment. Each of the facing systems was evaluated for four factors: (1) cost, (2) appearance, (3) durability, and (4) constructibility. The issue of public accessibility and safety is site-specific and may affect the choice of a stepped face versus a smooth sloping downstream face. This factor was not included in Table 3.1 but should be considered at any site.

Table 3.1. Design Factor Ratings for Downstream Facing Systems

Upstream Facing System	Cost	Appearance	Durability	Construct-ibility
1. Unformed RCC	Low	Poor	Poor	Routine
2. Formed RCC	Low	Poor/Fair	Fair	Routine
3. Formed Conventional Concrete Placed Concurrently with RCC	Moderate	Good	Good	Moderate
4. RCC Against Precast Concrete Panels	Moderate	Good	Good	Routine
5. RCC Against Precast Concrete Blocks	Moderate	Good	Good	Routine
6. Reinforced Concrete Cast After RCC Placement	Moderate	Very Good	Good	Difficult
7. RCC Against Slip-Formed/Extruded Concrete Facing Elements	High	Fair-Good	Good	Difficult
8. RCC Placed Concurrently with Fill Material	Low	—	Good	Routine
9. Mechanically Compacted Unformed RCC	Low	Poor	Fair	Routine

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