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OVERTOPPING PROTECTION FOR DAMS – A TECHNICAL MANUAL OVERVIEW

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Abstract

Inadequate spillway capacity is a common problem with many dams. Reservoir inflow that exceeds available storage and/or spillway discharge capacity can lead to dam overtopping, failure, and potential for loss of life and significant downstream damages. The design and construction of overtopping protection for dams is increasingly being viewed as a viable alternative to constructing larger spillways or increasing reservoir storage by raising the dam crest. The decision to pursue overtopping protection for a dam must give strong consideration to the risk of failure of the protection system, which could lead to a full breach of the dam. Overtopping protection should generally be reserved for situations with a very low annual probability of operation, and with physical or environmental constraints and a prohibitive cost of other flood protection alternatives. Hydraulic, structural, and geotechnical engineers, as well as geologists, should be involved throughout the design process.

Alternatives for overtopping protection may utilize a variety of different materials, such as roller-compacted concrete, conventional cast-in-place concrete, precast concrete blocks, gabions, turf reinforcement mats, vegetative cover, flow-through rockfill, reinforced rockfill, riprap, and various types of geosynthetic materials. Not all materials are applicable in every situation. In most cases, significant research and hydraulic testing has been conducted on these materials, but since most overtopping protection is designed to function at an infrequent recurrence interval, practical experience on constructed projects that have been subjected to overtopping flows is limited. New materials and methods of analysis are always being developed, so design engineers may need to rely upon manufacturers' design recommendations, always mindful of the limitations of product testing and analysis. This paper provides a summary of the most commonly used overtopping protection systems, and is an overview of a technical manual on overtopping protection for dams currently being developed by the Bureau of Reclamation (Reclamation) for the Federal Emergency Management Agency (FEMA).

Introduction

The original design of a dam may be reevaluated due to the availability of new information, the refinement of certain design criteria or guidelines, or as part of a regular dam

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safety program. During this process, the design flood may be revised, resulting in a flood that is larger than was used for the original design. In many cases, analysis may show that the revised flood will result in the dam being overtopped due to insufficient reservoir storage and/or release capabilities.

There are many methods available for accommodating larger design floods. However, some of these methods, such as increasing reservoir storage by raising the dam crest or increasing release capability by increasing the spillway discharge capacity, can often be cost prohibitive or impractical. To address this situation, new design approaches have been developed that allow for the dam to be safely overtopped. The design and construction of overtopping protection for dams is increasingly being viewed as a viable alternative to larger spillways as developing watersheds or changing hydrology produce higher peak flows and the need for additional spillway discharge capacity for existing dams. Overtopping protection may be an attractive alternative because of its potential economic advantages. Maintaining the existing hydraulic conditions at the dam is also increasingly important as downstream river corridors are developed in close proximity to the channel.

The decision to pursue overtopping protection for a dam must give strong consideration to the risk of failure of the protection system, which could very quickly lead to a full breach of the dam. This is especially true for embankment dams, in the sense that a small defect or design flaw could lead to catastrophic failure once the embankment is exposed to the overtopping flow. This type of risk needs to be incorporated into the decision-making process, whether qualitatively or quantitatively. A decision to use overtopping protection in place of improving the service spillway, imposing a reservoir restriction, raising the dam crest, or constructing an auxiliary spillway cannot be made lightly. Overtopping protection should generally be reserved for situations with some combination of very low annual probability of operation, physical or environmental constraints on constructing other methods of flood protection, and prohibitive cost of other alternatives.

Many organizations, such as the Bureau of Reclamation (Reclamation) and the U.S. Army Corps of Engineers (USACE) have conducted extensive model testing on a variety of overtopping alternatives. Often, the results of these studies are not well known outside of these organizations. Due to the absence of any single recognized standard for overtopping protection alternatives for dams, there is some inconsistency in the design and construction rationale. FEMA, as the lead agency for the National Dam Safety Program, sponsored the development of a technical manual on overtopping protection for dams in conjunction with Reclamation. The purpose of the manual is to: provide a nationally recognized source of information that is current and has a technical consensus; promote greater consistency between similar project designs; facilitate more effective and consistent review of proposed designs; and, aid in the design of safer, more reliable facilities.

Embankment Dam Overtopping Protection

General

One of the most common dam safety deficiencies for embankment dams is inadequate spillway capacity. Erosion and slope instability resulting from overtopping flow is a principal cause of embankment dam failure. Understanding the behavior of an embankment dam during an overtopping event provides a basis for the design of protective measures. Flow over an embankment generally proceeds from a subcritical velocity over the upstream portion of the crest, through critical velocity on the crest and supercritical velocity across the remainder of the crest, to accelerating turbulent flow on the downstream slope. Designers and dam safety personnel should fully evaluate all options available when embankment dam overtopping is a possibility. If an emergency spillway is to be selected as embankment overtopping protection, flow from the spillway should be safely directed to the downstream channel and away from the abutment groins in order to reduce the risk of erosion of the dam embankment during an overtopping event.

Before designing overtopping protection for an existing embankment dam, the potential impact of the proposed modifications must be evaluated. Any reductions to the embankment cross-section can decrease the factor of safety for slope stability, especially due to excavation required during construction. Excavation at the toe of the embankment to construct the various features of the overtopping protection, in particular for construction of a downstream stilling basin or for over-steepening of the downstream slope, will change the stability of the embankment and could increase the potential for internal erosion. An evaluation of the estimated risks of dam failure during construction should be performed as part of the design of overtopping protection for an embankment dam, and should involve geotechnical engineers as well as geologists.

Since 1983, extensive testing has been conducted in the United States, Great Britain, and the former Soviet Union to develop alternatives for overtopping protection for embankment dams. General design considerations when selecting an overtopping protection type or material include: unit discharge, maximum head, embankment height, flow velocity, surface discontinuities, erosion potential, aesthetics, economics, potential for debris loads, durability, energy dissipation, and potential vulnerabilities or risks. Overtopping protection systems for embankment dams have been constructed using various types of construction materials. The following are the most commonly used overtopping protection systems for embankment dams.

Roller-Compacted Concrete

Roller-compacted concrete (RCC) has been utilized in dam construction since the late 1970s. The development of RCC technology has provided a successful method of erosion protection for embankment dams, which has proven to be cost effective while affording a number of other advantages, including very rapid construction with minimal project disruption. In most cases, construction for overtopping protection is limited to the dam crest and downstream slope, with no requirement for reservoir restrictions. Depending upon the site conditions and discharge requirements, the entire length of the embankment dam can be used as an emergency spillway by armoring the crest and downstream face with RCC, or a selected portion of the embankment crest can be lowered for use as an RCC-lined spillway. RCC spillways generally consist of non-air-entrained concrete, without reinforcement, water-stopped joints, or anchorage, but with underdrain systems similar to conventional concrete spillways. RCC overtopping protection for embankment dams is generally limited to emergency spillways that would only operate for flood return periods of 100 years or greater.

RCC has a wide application for use as overtopping protection since the material is suitable for a wide range of flow depths and velocities. Laboratory studies, full-scale tests, and field experience have all shown that, even at relatively low strengths and cementitious contents, RCC has exceptional resistance to cavitation, erosion, and abrasion damage from both high and low velocity flows, even at an early age. RCC can generally resist captured debris impacts (such as trees, cobbles, and boulders) without significant damage and without causing severe irregularities in the hydraulic flow due to snagging of debris. RCC overtopping projects completed in the United States generally range in height from 15 to 65 feet, with the volume of RCC typically ranging from 1,000 to 60,000 yd^3. The typical project averages 35 feet high, with an average RCC volume of 8,000 yd^3, an average spillway discharge of

80 ft^3/s per lineal foot width of spillway, and an average design overflow depth of 5 feet. A list of 70 completed RCC overtopping protection projects was included in a design manual for RCC spillways and overtopping protection prepared by the Portland Cement Association (PCA) in 2002 [1].

RCC is typically placed in horizontal lifts on the downstream slope, resulting in a stepped chute. Stepped chutes significantly increase the rate of energy dissipation on the downstream face of the dam compared to a smooth spillway having the same slope, with total head loss of up to about 73 percent, depending upon step height, flow depth, and other factors. This reduces the size required for the energy dissipation structure (downstream apron or stilling basin) and the potential for scouring the downstream channel and/or foundation material. The required thickness of the RCC chute is based upon the slope of the spillway, constructability requirements for placement of the RCC, and structural requirements to resist potential uplift pressures and other loading conditions. A minimum 8-foot-width is normally required for the horizontal lift surface to operate standard placing and compacting equipment. Depending on the slope of the embankment, this provides an effective concrete thickness of 2.3 to 3.2 feet. Concrete training walls must be constructed along the sloped chute to contain the spillway flow and protect the dam embankment from potential erosion, unless abutment protection is located along the downstream embankment groins. Converging walls may require additional analysis.

Seepage through RCC lifts can be designed to be safely handled by a properly designed drainage system beneath the sloped RCC chute. Contraction joints may be placed in wide RCC spillways to control the location of cracks caused by thermal contraction of the RCC, with a typical spacing from 100 to 300 feet. RCC spillway crests that follow the shape of the embankment crest to simplify construction represent a broad-crested weir having a low coefficient of discharge. Increasing the efficiency of the spillway crest section can reduce the required crest length of the spillway and/or the flow depth. Conventional concrete can be used to provide an ogee-shaped crest or a sharp-crested weir to improve the spillway discharge coefficient. An upstream cutoff wall is generally recommended to increase the seepage path between the RCC approach apron and soil interface. The downstream apron or stilling basin is a critical feature of an RCC spillway located on a dam embankment, and must be designed based on the flow depth and incoming velocity, unit discharge, operating frequency, tailwater conditions, foundation conditions, erosion control requirements, and downstream consequences. A downstream cutoff wall should be sized to prevent undermining of the spillway from channel erosion. A typical section of RCC overtopping protection for an embankment dam is shown in Figure 1. A vegetated soil cover can be added to provide a more natural appearance.

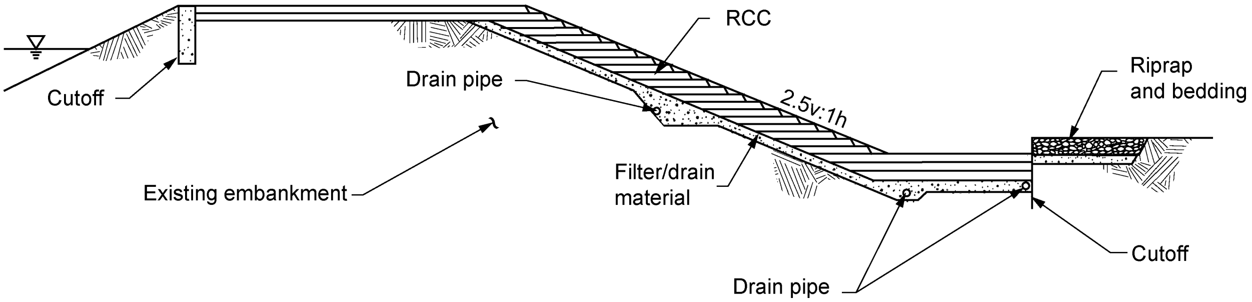

Figure 1. Typical section, RCC overtopping protection (PCA, 2002)

Conventional Concrete

Overtopping protection for embankment dams utilizing conventional reinforced concrete relies on a continuous layer of concrete to serve as the flow surface for reservoir releases and to protect the underlying embankment from high velocity flows. Guide walls are normally provided at the sides of the overtopping protection to contain the overtopping flows and to protect the abutments. In order for conventional concrete to be effective as overtopping protection, the concrete layer must remain intact and be free of significant defects during a flood event. Although not common practice, there are several examples worldwide of concrete chutes and box conduits located on the downstream face of embankment dams, serving as both service and emergency spillways, as noted in the manual. The concrete slabs generally have a minimum thickness of 12 inches and include reinforcing steel. The operating history of these structures is very limited and their performance is largely untested. Excessive settlement of the underlying embankment may affect the structural integrity of the concrete by causing cracking or offsets at joints (as may also be the case for RCC).

Flood routings are performed for various frequency floods to determine the magnitudes and durations of overtopping flows, and water surface profiles are developed to calculate flow depths and velocities at various locations for the spillway or concrete overtopping protection. This information is used to design the chute guide walls and stilling basin, and to evaluate the potential for stagnation pressure development, cavitation, and air entrainment within the chute. If durations of overtopping flows are limited, spillway failure may initiate but may not have time to fully develop into a breach of the reservoir. General design information for concrete spillways is provided in Reclamation's *Design of Small Dams* (1987) [2].

Stagnation or uplift pressures can cause catastrophic failure of the concrete overtopping protection as a result of water flowing into open joints and cracks during reservoir releases. If water entering a joint or crack reaches the concrete bedding materials or embankment surface, failure can result from excessive uplift pressure on the concrete slab and/or by erosion of the underlying materials. If the drainage system is inadequate and the slab is insufficiently restrained, the uplift pressure can cause hydraulic jacking and progressive loss of the concrete overtopping protection. If drainage paths are available, but are not adequately filtered, erosion of foundation material is possible and structural collapse may occur. Concrete deterioration resulting from delamination, poor consolidation, alkali-silica reaction (ASR), freeze-thaw damage, frost heave, and sulfate attack can exacerbate this potential failure mode by initiating cracks and concrete spalls, opening joints, creating offsets into the flow, and causing separation of the slab from the foundation. Defensive design measures include joint waterstops and keys, transverse cutoffs, reinforcement crossing transverse joints, soil anchors, filtered underdrains, and rigid plastic foam insulation, as shown in Figure 2.

Cavitation damage can occur along flow surfaces exposed to high velocity flow where the flow durations are long and the water pressure is reduced locally because of an irregularity in the flow surface. An air slot or ramp can be provided to introduce air into spillway flows at critical locations to reduce the potential for cavitation damage to concrete.

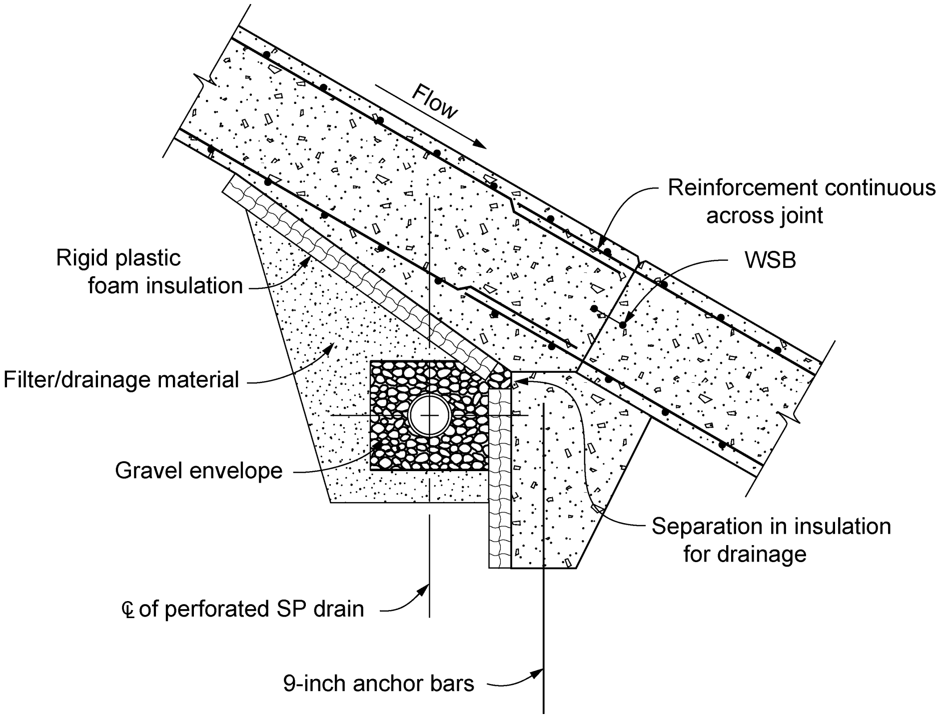

Figure 2. Defensive design measures for concrete overtopping protection slab.

Precast Concrete Blocks

Precast concrete blocks, often referred to as articulated concrete blocks (ACBs), are used over earthen materials to provide a hard surface for overtopping flow to pass safely without eroding the underlying earthen materials. An ACB system is comprised of a matrix of individual concrete blocks placed together to form an erosion-resistant revetment with specific hydraulic performance characteristics. The term “articulated” implies the ability of the matrix to conform to minor changes in the subgrade while remaining interconnected with geometric interlock and/or with additional system components, such as cables, pins, or mats.

There are many types of precast concrete blocks used for overtopping protection, each with its own geometry, useful application based upon hydraulic performance and erosion prevention, installation procedures, maintenance requirements, aesthetic value, and cost. Of primary importance for overtopping protection is to select a commercial product that has been tested under the flow conditions expected during overtopping, and to ensure that an adequate filtered drainage layer is provided beneath the block system. Typical applications may experience high flow velocities, moderate flow depths, hydraulically steep slopes, and possibly tailwater and energy dissipation on the flow surface. The main types of articulated concrete blocks are described below:

Cable-tied Blocks

1. Concrete blocks that are individually formed, with or without open areas, and are laced together with cabling at the factory into large, sometimes uniquely shaped mattresses for installation. They are cabled together, running both longitudinally and laterally, at the factory and brought to the site on flat-bed trucks for placement as a unit using a crane. Examples of U.S. manufacturers include Armortec, Petraflex, and International Erosion Control Systems.

2. Articulating Block (AB) mats form cable-reinforced concrete block mattresses that resist erosive forces. The AB fabric form consists of a series of compartments linked by an interwoven perimeter. Grout ducts interconnect the compartments, and high strength revetment cables are installed between and through the compartments and grout ducts. Once filled with concrete, the AB mats becomes a mattress of pillow-shaped, rectangular concrete blocks. The cables remain embedded in the concrete blocks to link the blocks together and facilitate articulation. AB mats are manufactured by Hydrotex and Texicon.

Interlocking.—Concrete blocks that are individually formed with mortise and tenon-type features that are fit together on site. Some types have open area and some are solid. Although some also have cabling, this category is generally hand-placed or sometimes brought to the site on geotextile mats. Examples of U.S. manufacturers are Conlock II and Trilock.

Overlapping.—Concrete block units that are tapered wedge block shapes or concrete slabs that are overlapped shingle-fashion from the toe of the revetment to the crest. Individual units in the system are staggered and interlocked for enhanced stability. Each row of units are laterally offset by one-half of a block width from the adjacent row. When placed, the blocks form a stepped surface with slots providing open areas for venting subgrade uplift pressures. They are normally hand-placed, but have also been cabled together on site. Contech, Inc. currently holds the exclusive license in the United States for the ArmorWedge concrete block units developed by Reclamation.

All types of precast concrete blocks, except AB mats, are manufactured at a precast facility using a high volume steel mold for standard applications. Most ACBs are from 4 to 9 inches in thickness (measured normal to the slope). Each product may or may not have an open area equal to anywhere from 2.5-5 percent for the wedge-shaped blocks, to 18-35 percent for other types of blocks. Some varieties of blocks rely on a vegetative cover within the open areas of the blocks to improve performance. All products require placement over a smooth subgrade with a geotextile and/or a bedding or drainage layer between the subgrade and the block system. Installation requirements and techniques vary with the product and will affect product performance. System failure is defined when the blocks lose sustained intimate contact with the subgrade, when tested in accordance with ASTM D7277-08. Methods for computation of unit discharge, flow depths, friction slope, cross-sectional averaged flow velocity, and boundary shear stress are detailed within ASTM D7276-08, along with guidelines for qualitative assessment of stability. Most testing has been performed and prototype installations constructed with parallel walls, whether vertical or trapezoidal. If the spillway walls converge, additional physical or numerical modeling should be performed to assure flow velocities and directions are not exceeding tested design limits.

The first application of cable-tied ACBs for overtopping protection on embankment dams in the U.S. was at three National Park Service (NPS) dams on the Blue Ridge Parkway in North Carolina. The dams range in height from 28 to 40 feet, with crest lengths from 270 to 530 feet and design unit discharges from about 7 to 30 $ft^3/s/ft$, with computed flow velocities up to 26 ft/s on 2:1 slopes, but they have never been exposed to overtopping flows. Current design and installation standards for cable-tied ACBs were prepared by the National Concrete Masonry Association (NCMA) in 2006 [3]. A typical installation is shown in Figure 3. The crest detail must not allow water from the reservoir under the system and must be well anchored. If utilizing a wedge-shaped or individual block system, the first row of blocks should be overlapped and held in place by a concrete crest cap. The toe and groin area treatments must be sufficient to pass expected seepage and drainage flow, to provide support for the block system, and prevent undermining of the system. The presence of a hydraulic jump on the blocks based on tailwater elevation and hydraulic calculations must be considered in the design. Soil anchors used to be routinely installed with early cable-tied systems, but currently they may be considered an extra measure of conservatism. The cables are usually stainless steel, galvanized steel, or polyester, and all have performed competently in testing and field installations, but with limited years of service.

Figure 3. Placement of cable-tied mats over a geotextile on the downstream face of Strahl Lake Dam, Indiana (Photo by Contech Construction Products, Inc.)

Vegetation and Turf Reinforcement

Vegetative cover maintained on the upstream and downstream faces of small dams provides protection against weathering effects and rill development due to rainfall on the embankment. During overtopping flow, vegetation can also provide protection against the initiation of concentrated erosion that leads to headcut development and dam breach. For larger flow rates, vegetation may delay breaching sufficiently to permit evacuation of downstream areas, as shown in Figure 4. Vegetative cover is most viable as a protection method in humid climates that receive sufficient moisture to establish relatively dense, uniform turf grasses without supplemental irrigation. Good maintenance of the cover is essential to achieve significant protective benefits. Vegetation is not suitable for very steep embankments because of the difficulty of performing mowing and other maintenance required to achieve uniform cover. Installation costs for vegetation are often lower than for other forms of overtopping protection, but maintenance costs can be higher and performance may be limited.

Vegetation provides protection to an embankment in two functional ways: (1) protection of the soil surface by reduction of velocities and stresses at the embankment boundary as a result of the coverage provided by stems and leaves that lay down in the flow and blanket the surface; and (2) the reinforcement of the underlying soil due to the presence of plant roots. The reinforcement aspect may be further improved by the use of turf reinforcement mats that can improve root mass continuity following full vegetation establishment. Some types of turf reinforcement may also provide a soil surface protection benefit before grass becomes fully established. The analysis of unreinforced vegetation for overtopping protection can be accomplished using procedures described by Temple and Irwin (2006) [4]. The best source for unbiased information about commercial turf reinforcement products is Hewlett et al. (1987) [5].

Figure 4. Vegetated embankment experiencing overtopping flow.

Reinforced Rockfill

Reinforcement can be incorporated into rockfill to hold the surface rock particles in place under overtopping flow conditions. Improvement to the overall mass slope stability is a secondary benefit. The rockfill reinforcement is generally composed of two essential components: the mesh and an anchorage system. The mesh is located on the outside of the rockfill and is intended to hold the rock particles on the outer embankment slope in place, while the anchors are attached to the mesh and embedded deep within the rockfill to hold the mesh in place. Even though the anchors will add some tensile strength to the slope, this is not necessarily relied upon for global slope stability. However, the tensile strength of anchor bars is sometimes relied upon in the mass slope stability analysis to counter the effect of pore pressure increases caused by the flow over the dam.

There are four essential parts to the analysis and design of a rockfill dam subject to overtopping: 1) flow over, 2) flow through, 3) mass slope stability, and 4) filter compatibility. Designs to accommodate flow over a dam are much more stringent than those to accommodate flow through a dam because velocities of water flowing over a rockfill dam can be ten times higher than flow through velocities. The reinforcement of rockfill dams for overtopping protection is ordinarily designed empirically, that is, by copying designs of older dams performing successfully. Pit 7 Afterbay Dam in California is an early design for a rockfill with reinforcement that has been used as a basis of design for many subsequent rockfill dams. However, no example has been found in the literature of using reinforced rockfill to protect an existing earthen dam from overtopping flows.

Mesh material types include chain link fencing and welded wire, but mesh usually consists of steel reinforcement bars tied together. The size of the mesh opening is relative to the smallest rock that could be dislodged from the downstream outer face of the embankment slope. The mesh should have sufficient strength to resist the tractive and seepage forces acting on the surface particles. If overtopping occurs, the mesh needs to also withstand the impact forces of debris carried by the overflow. Chain link fencing is weak and vulnerable to such impacts. Heavy reinforcing steel (such as No. 7 bars) is relatively resistant to damage from overtopping debris. To best prevent debris from catching on mesh of steel reinforcement during overtopping, horizontal bars are placed against the fill and the vertical bars are attached above the horizontal steel. Large rockfill reduces the cost of reinforcement by allowing more widely spaced steel bars. Bars do not have to be spaced equally horizontally and vertically as was the case at Pit 7 afterbay, where No. 7 bars were spaced at 10-foot centers on the horizontal and at 1-foot centers on the vertical. The horizontal bars are connected to the vertical bars where they cross with clamps or other devices to maintain the shape of the mesh.

The surface reinforcing grid or mesh is affixed to the embankment slope with anchor bars, as shown in Figure 5. The anchor bars are embedded into the embankment beyond the critical shear surface to a depth sufficient to transfer the design loads in the bars to the surrounding rockfill and eliminate the possibility of premature pullout. This surface may be approximated by a line parallel to the downstream slope into the fill a distance equal to 2/3 of the embankment height; however, this is not always adequately conservative, depending on the height of the embankment and the friction of the materials. Mass slope stability analysis should also be performed to determine the required depth of embedment. Alternatives to embed the anchors into the rockfill include crank-shaped anchors, anchors fixed to grouted dowels in the fill, and inclined anchors. Vertical spacing of anchor bars should be close enough to prevent the critical shear surfaces from exiting between the layers of reinforcement. The reinforcement system is connected to the foundation and abutments with rock bolts or another solid means to keep it in place along the edges where the erosive forces may be the most aggressive.

To resist through flow, the reinforcement should extend well above the height of the seepage exit elevation. To resist flow over an embankment, the reinforcement should extend over the entire downstream face, abutment to abutment. Designs should also assure crest stability during overtopping. Any discontinuities or flow concentrations on the crest or slope would be a location of more turbulence and excessive erosion attack that could over-tax any protection system. Flow concentrations are especially problematic around structures or depressions, at the ends of crest camber, in the abutment groins, or at the embankment toe. These are areas where overtopping protection needs to be the strongest. Rockfill would be largest and reinforcement would be heaviest at the downstream toe of an embankment subject to overtopping.

The reinforcement can degrade with use and over time. Surface meshes can be damaged by rocks and logs in overtopping flows. Steel reinforcement can become corroded. Carbonaceous rockfill materials should be avoided due to their galvanic effect and because of their high electrical conductivity. Should reinforcement become buried by saturated soils, corrosion will be influenced by the quality and pH of the water, soluble salt content of the overlying soil, and aeration. Conventional practices to fight against corrosion include: substitution of nonmetals for metal reinforcement; use of corrosion-resistant metal alloys; use of protective coatings such as zinc or fusion-bonded epoxy; installation of corrosion monitoring systems; and cathodic protection.

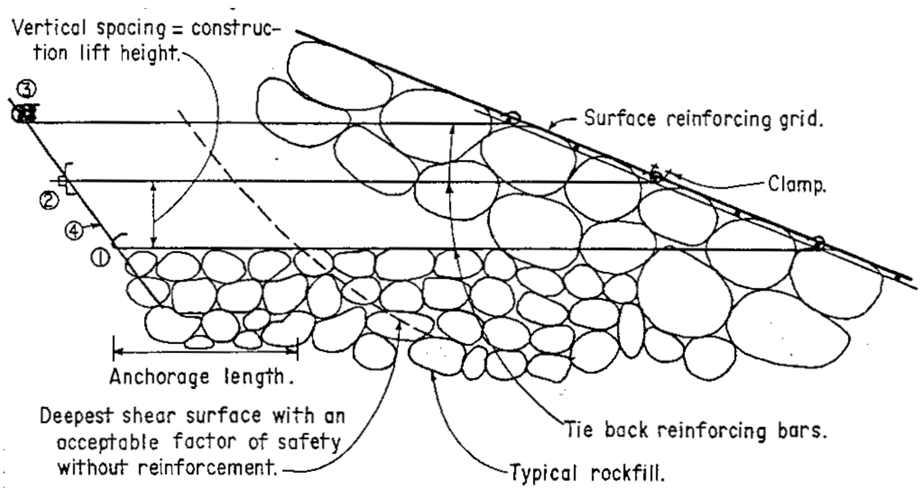

Figure 5. Schematic detail of steel reinforcing bars with tie-back anchor alternatives (Brown et al., 1983) [6].

Riprap

Riprap is often used on the slopes of embankment dams to prevent erosion due to natural rainfall, surface runoff, and wave action in the reservoir. In recent years, riprap on the downstream slope has been recognized to have some capacity to prevent the initiation of embankment erosion during overtopping flow. Riprap is generally composed of high quality crushed or quarried rock (typically granite or limestone) with relatively uniform size. Flow is conveyed through, and in some cases above, the riprap layer installed over bedding. This system prevents erosion by reducing flow velocities and hydraulic stresses directly against the surface of the erodible embankment materials. Riprap is relatively economical compared to other options and is a popular slope protection option for arid areas and on steeper embankment slopes where vegetation is difficult to establish and maintain. As overtopping protection, riprap is most cost effective for lower flow rates and flatter slopes, which do not demand extremely large rock sizes. Riprap has been specified for the protection of small, low hazard dams, but at this time there are no known applications of riprap specifically designed for overtopping flows on significant or high hazard dams. Hydraulic testing has developed guidance for estimating energy dissipation due to riprap and for specifying stone size and layer thickness. The most notable recent contributions have been from Abt and Johnson (1991) for slopes up to 20% [7], Robinson et al. (1998) for intermediate slopes up to 40% [8], and Frizell et al. (1998) for slopes up to 50% [9]. A design procedure focused on flat slopes (up to 20%) was provided in the USACE's Hydraulic Design of Flood Control Channels (EM 1110-02-1601) (1994) [10].

Good quality control of materials and installation procedures are essential for obtaining good riprap performance. Specifications can be difficult to maintain during production, especially as rock sizes increase. It is especially important to maintain cleanliness of materials and prevent size segregation during handling and placement. Since a large fraction of the flow is conveyed within the riprap layer, long-term performance could potentially be affected by infiltration of fine materials into the riprap layer (e.g., sediment or vegetation). Degradation of rock over time due to weathering can also affect long term performance, but this should not be an issue if high quality materials are used. Flow transition areas at the toe, crest, and groins are potentially vulnerable, although testing that has included crest and toe areas has shown thus far that failure of the riprap will occur first on the slope. The use of the rock chute concept tested by Robinson et al. (1998) can eliminate the issue of flow converging in groin areas, but also limits the overtopping flow section to the width of the downstream waterway, as shown in Figure 6.

Figure 6. Rock chute spillway on Little Washita Site 13 in Grady County, OK (photo courtesy Chris Stoner, USDA-NRCS).

Concrete Dam Overtopping Protection

General

The basic types of concrete dams are gravity, arch, and buttress dams. Potential concerns for overtopping of concrete dams of all types generally involve blocky or erodible rock abutments or foundations, rather than concerns for the structure itself. In these cases, overtopping protection may be required for the exposed abutments and foundation within the impact zone of the overtopping flow, to prevent the loss of materials and subsequent undermining of the dam which could otherwise result in instability and failure. Alternatively, higher hydrostatic loads on concrete dams resulting from the passage of a flood event could produce lower factors of safety for sliding at a lift line within the body of the dam, at the dam-foundation contact, or along a potential slide plane within the foundation, requiring some form of concrete buttress or reinforcement. The following are the most commonly used overtopping protection systems for concrete dams.

Roller-Compacted Concrete

The use of RCC for overtopping protection of a concrete dam is typically to provide a massive downstream buttress for the structure to improve sliding stability. RCC buttresses have been constructed by Reclamation for a straight masonry gravity dam (Camp Dyer Diversion Dam in Arizona), for a curved concrete arch dam (Santa Cruz Dam in New Mexico), and for a concrete overflow spillway structure (Pueblo Dam in Colorado). In each case, RCC was placed in horizontal lifts along the downstream face of the existing structure to improve the stability of the structure for the design loads. The downstream face of the RCC buttress can be stepped to provide energy dissipation of the overtopping flow, reducing the design requirements for the terminal structure. Drainage pipes may be required at the foundation and structure contact surfaces to collect future seepage and relieve potential uplift pressures. Contraction joints can be provided for crack control.

General construction considerations for RCC buttresses are similar to those for other types of RCC construction. An RCC buttress for a concrete dam will not require upstream forming, but will require special surface preparation and treatment for the upstream contact surface, which may consist of cleaning using a high-pressure water jet, and the use of a special concrete mix to ensure bond between the RCC and the existing structure, without mechanical anchorage. If the RCC buttress is constructed against a sloping concrete dam face, the buttress width may be fairly constant for the full height of the structure. Sufficient sliding resistance due to friction and cohesion must be provided by the buttress at the lift lines. For Pueblo Dam, high strength rock bolts were used to reduce the tensile stresses that could develop in the RCC buttress, and to provide additional active resistance across the foundation failure surface.

RCC may also be used to protect the dam foundation from erosion and headcutting from an impinging jet as for conventional concrete, but would not lend itself to the protection of steep abutments.

Conventional Concrete

Conventional or mass concrete can be used to provide overtopping protection in the form of concrete overlays constructed on the exposed rock foundation. The overlays protect the dam foundation from overtopping flows that could pluck rock blocks from the surface or that could mine and remove material along shears or faults within the dam foundation. Erosion of the rock surface could lead to headcutting and undermining of the foundation directly beneath the dam or it could allow foundation wedges to daylight and become unstable. Concrete overlays can protect the foundation from impinging flows or from overtopping flows that collect and flow down the groin of the dam to the river channel.

Concrete overlays should be designed to protect the foundation from erosion and minimize uplift pressure from seepage of water beneath the slab. Slab thickness and reinforcement requirements will be dependent on the loading conditions identified. In most cases, the slab should be continuously reinforced to control cracking, with waterstops provided at control joints. A foundation drainage system should be provided below the slab to minimize development of uplift pressures. Anchor bars may be provided to ensure the concrete protective slab remains firmly attached to the foundation. Overtopping protection for concrete dams should be designed for the following loads:

> *Impinging Jet Impact Load* – Impact loads from impinging jets may induce compressive, shear, and bending stresses in protective slabs. Impact pressures may be estimated on foundation areas without tailwater using the Bernoulli equation, converting the static head to a pressure head. Flow aeration and reducing the angle of impingement will reduce the actual pressure on the foundation.
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> *Uplift Due to Impinging Jet* – Impinging jets entering open joints in the foundation or open cracks in a protective slab may develop local uplift pressures equal to the full reservoir head if the foundation is not adequately drained.
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> *Steady State Uplift* – Seepage under reservoir head will produce an uplift pressure distribution between the upstream face of the dam and the downstream end of the protective slab. The protective slab should be designed to resist the maximum loads

from the uplift pressure distribution, but generally not less than 10 feet of design head. Where seepage problems are known to exist, uplift pressures should be determined from finite element models calibrated to available instrumentation data. For preliminary or final designs, where seepage problems do not exist, uplift pressures may be assumed to vary uniformly between the upstream face, using full reservoir head; the drainage gallery, using tailwater head plus the difference between the reservoir and tailwater heads multiplied by a drainage effectiveness factor; and the downstream end of the protective slab, using full tailwater head. The drainage effectiveness factor is usually taken as one-third to one-half, depending on the quality of the drains and their accessibility for periodic maintenance.

When concrete overlays are placed on the downstream foundation areas, the foundation will need to be prepared for concrete placement. This will involve removing loose and weathered foundation materials so that a sound surface can be achieved. If a determination is made that the foundation is not as competent as expected and if the unprotected portions of the foundation will be exposed to potentially erosive flows, consideration should be given to extending the concrete overlays.

Concrete overlays can be very effective in protecting portions of the foundation exposed to overtopping flows by sealing the surface of the foundation and preventing high velocity flow from entering joints and fractures in the rock and initiating plucking of the foundation rock. To be effective, the overlays will need to extend over the areas impacted from overtopping flows (which will change with the depth of overtopping flows and will be a function of the flood magnitude); remain intact during large flood events; and be able to retain its integrity under the environmental conditions to which it is exposed. Hydraulic studies of the overtopping flows will be needed to ensure that the coverage of the overlays is adequate. Good quality control measures during foundation preparation and concrete placement, and regular inspections of installed concrete overlays will be needed to ensure that the overlays remain capable of withstanding overtopping flows.

An example of conventional concrete overtopping protection is Gibson Dam, a concrete gravity arch dam about 200 feet high where concrete overlays having a minimum thickness of 2.5 feet were added by Reclamation to provide protection for the abutments during overtopping flows.

Plunge Pools

Plunge pools can be an effective and economical way of dissipating energy from overtopping flows for concrete dams and preventing erosion of the dam foundation. A plunge pool can be provided through excavation downstream of a concrete dam, or created by overtopping flows and then stabilized as the energy of the overtopping flows and the resistance of the rock forming the plunge pool reach equilibrium. Tools are available for predicting the characteristics of falling jets and the ability of jets to erode rock foundations, either due to direct impingement or after travelling through a tailwater pool. The erosive power of the jet is dependent on a number of variables, including: the initial depth, velocity, discharge aeration, turbulence, angle of issuance and shape of the jet; breakup of the jet; aeration and spread of the jet; jet velocity, depth and angle at impingement with the plunge pool or rock abutment; and, the dispersion and/or spread of the jet in a plunge pool.

Analysis methods are available for determining the jet hydraulics in the air, at the impingement with a rock foundation, or at the impingement and potential dispersement in a pool. Jets impinging on a rock abutment will transfer forces to the surface and into the cracks, faults, or joints of the rock. Jets falling into a pool below the dam may disperse within the pool before impinging on the rock. If the overtopping flow jet disperses either due to the height of the fall or due to the depth of the tailwater pool, reduced energy will be available to erode the rock foundation. If the jet does not disperse, the rock foundation may scour, depending on the characteristics of the rock. Analysis techniques are available to predict the depth of scour from impinging jets and to identify the failure mechanism that leads to rock scour (e.g. brittle fracture, fatigue failure, or dynamic implusion). An unlined plunge pool was designed by Reclamation for the new spillways at Theodore Roosevelt Dam in Arizona.

The proper design of a plunge pool requires a team of designers capable of determining the hydraulics of an overtopping jet and the geologic features of the rock with as much accuracy as possible. This may require drilling to determine the rock characteristics and/or review of construction photos of the abutment and foundation areas for an existing dam. Judgment is required by designers to properly apply the methodology for designing plunge pools. The duration of the overtopping flows is an important parameter that is not directly accounted for in available design methods.

Conclusions

Designers must continue to explore and investigate the subject of overtopping protection of dams. This paper provides a summary of the most commonly used overtopping protection systems for both embankment and concrete dams. Since no single publication can cover all of the requirements and conditions that can be encountered during design and construction of overtopping protection systems, it is critically important that when an overtopping protection alternative is considered, the designer must clearly understand all aspects of its design, construction, and long-term maintenance needs. Hydraulic, structural, and geotechnical engineers, as well as geologists, should be involved throughout the design process. The guidance in this paper or the technical manual should not be used without first securing competent advice with respect to its suitability for any given application. There are regulatory restrictions in some states that prohibit the use of overtopping protection, while other states allow certain types and others have no policy. In any case, it is the designer’s responsibility to develop the required engineering design details to ensure acceptable performance of the system under the design loading conditions.

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