embankment dams has become more fully developed and accepted. Performance can be further improved by the use of geotextile fabrics, meshes, or reinforcement mats through which the grass can grow, but will be dependent upon good grass cover.

Geomembrane liners and geocells

A geomembrane liner can be placed on a smooth subgrade with the sides and upstream and downstream ends trenched and buried beneath a granular soil cover for overtopping protection of low embankments. Geocells backfilled with concrete, and fabric-formed concrete can also provide protection.

Case histories of overtopping protection projects

Selected case histories of various types of overtopping protection alternatives for both embankment and concrete dams are included in appendix to this manual, with references.

Conclusion

Some of the overtopping protection systems included in the technical manual may not be considered appropriate for use on significant or high hazard potential dams by some regulatory agencies, at least until more performance data are collected. The designer of any overtopping protection project must clearly understand all aspects of its design, construction, and anticipated future performance, and must determine whether there are any regulatory requirements or constraints that may limit the types of overtopping protection systems available for further consideration.

How can you obtain a copy of the technical manual?

The *Technical Manual: Overtopping Protection for Dams* is available in DVD format. The DVD format includes hyperlinking, search capabilities, and PDF copies of cited references in the technical manual from Government websites and available for public use.

For information on how to obtain the DVD version of this technical manual, go to the FEMA website at:

www.fema.gov/resource-document-library

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Overtopping Protection for Dams

Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair

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Introduction

Inadequate spillway capacity is a common problem with many dams. Thousands of dams throughout North America have been determined to have inadequate spillway capacity and would be overtopped during the inflow design flood (IDF). Dam failure from overtopping can lead to a potential for loss of life and significant downstream damages.

There are many potential methods available for accommodating larger design floods. However, some of the more common 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 may 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.

The Federal Emergency Management Agency (FEMA) National Dam Safety Program sponsored the development of a technical manual, in conjunction with the Bureau of Reclamation, to collect and disseminate useful and relevant information regarding the design, construction, and performance of overtopping protection alternatives for embankment and concrete dams.

When should dam overtopping protection be considered?

Overtopping protection may be an attractive alternative for an existing dam because of its potential economic advantages, and may offer an economical solution to a hydrologic deficiency that would otherwise not be addressed. Maintaining the existing hydraulic conditions at a dam to the extent possible is also increasingly important as downstream river corridors are developed in close proximity to the channel.

The decision to pursue overtopping protection for an existing dam must give strong consideration to the potential risk of failure of the protection system, which could 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. An evaluation of this type of risk

Reinforcement can be incorporated into rockfill dams to hold the surface rock particles in place during overtopping and flow-through conditions. Improvement to the mass slope stability is also a benefit, but is considered secondary. The reinforcement is composed of a surface mesh to hold the rocks in place, and anchor bars attached to the mesh and embedded deep within the rockfill to hold the mesh securely in place. Reinforced rockfill is commonly associated with new construction. An example is the Pit No.7 Afterday Dam in California after many years of overtopping flow.

Riprap has long been used for embankment dams to prevent rill erosion of slopes due to surface runoff and to prevent wave erosion at the interface between embankment slopes and standing water. Riprap has been widely used in arid areas and on steeper embankment slopes (up to about 1.5:1) where vegetation is difficult to establish and maintain.

In recent years, riprap has been specified for the protection of small, low hazard dams with flatter slopes during small overtopping events of short duration. The use of riprap for high flow rates and steep slopes generally becomes cost-prohibitive due to the large size of rock required.

Vegetation and reinforced turf

Although vegetative protection has long been provided on embankments, it was not until the mid 1980s that engineers began to accept that it could have value beyond the purpose of weather protection. Research to determine the limits of vegetation performance in earth spillways led to methods for predicting the thresholds of vegetation failure. Further testing in steep channels showed that vegetation can provide significant protection against the onset of headcut erosion. In recent years, the concept of an allowable amount of limited overtopping flow for value, and cost. It is important to select a product that has been tested under the flow conditions expected during overtopping. Examples include cable-tied ACBs for Strahl Lake Dam in Indiana, (below)

and tapered wedge blocks for Friendship Village in Missouri (below).

Rock systems – gabions, reinforced rockfill, and riprap

Gabions are rectangular-shaped baskets or mattresses fabricated from wire mesh, filled with rock, and assembled to form overflow weirs, hydraulic drops, and overtopping protection for small embankment dams. Gabion baskets are generally stacked in a stair-stepped fashion, while mattresses are generally placed parallel to a slope. Gabions have advantages over loose riprap because of their modularity and rock confinement properties, thus providing erosion protection with less rock and with smaller rock sizes than loose riprap.

Gabions can conform to ground movement, can be easily constructed and repaired, can dissipate energy from flowing water, and can be designed to drain freely. However, permeability may reduce over time as the voids in the rockfill become progressively filled with silt, promoting vegetation growth. The wire mesh may be subject to abrasion and corrosion damage, requiring more frequent maintenance and repair than other protection systems.

must 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 occurrence (e.g. 1 in 100), physical or environmental constraints on constructing other methods of flood conveyance, and prohibitive cost of other alternatives; or where the downstream consequences of dam failure are demonstrated to be low. A careful analysis of all potential failure modes for the dam and appurtenant features must be performed. Overtopping protection is generally discouraged for use on new embankment dams due to settlement concerns, unless they can be addressed in the design and no practical alternatives exist.

What overtopping protection alternatives are available?

Alternatives for overtopping protection for dams may utilize a variety of different materials, such as roller-compacted concrete, cast-in-place concrete, precast concrete blocks, gabions, vegetative cover, turf reinforcement mats, synthetic turf revetments, flow-through rockfill, reinforced rockfill, rock reinforcement, riprap, and various types of geosynthetic materials including geomembranes, geocells, and fabric-formed concrete. Not all materials are applicable in every situation. Many are applicable only to embankment dams.

Significant research and hydraulic testing has been conducted on many of 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 to date. New materials and methods of analysis are always being developed, so designers may need to rely upon manufacturers' design recommendations for these new materials, always mindful of the limitations of product testing and analysis. Independent analysis should always be considered as appropriate.

The *Technical Manual: Overtopping Protection for Dams* assumes that a hydrologic deficiency exists at a dam and that traditional approaches to safely accommodate a larger design flood have first been investigated. The manual describes the types of overtopping protection systems that have been considered or used for embankment and concrete dams, including a historical perspective of their development and use, design and analysis guidance, construction considerations, maintenance, and a discussion of their potential vulnerabilities and risks, including summaries of their performance to date.

Cast-in-place concrete systems – RCC and CRCS

Roller-compacted concrete (RCC) has been widely used as overtopping protection for both embankment and concrete dams for a wide range of dam heights, flow depths, and velocities. RCC overtopping protection for embankment dams was first applied in the early 1980s at projects where rapid construction and/or budget constraints were driving forces in identifying alternative designs. The cost effectiveness of RCC overtopping protection was proven in these early projects where the relatively high hauling, placement, and compaction production rates yielded lower unit costs than for conventional concrete spillways. The RCC is commonly placed in horizontal lifts, with either formed or unformed steps. It remains a popular alternative today for embankment dams where a hard armor solution is desired. Examples include Vesuvius Dam in Ohio (cover photo) and Tongue River Dam in Montana (below).

The most common use of RCC for overtopping protection of a concrete or masonry dam is to provide a massive buttress for the structure to improve sliding stability. RCC may also be used to protect the dam foundation from erosion and headcutting from an impinging jet, but would not lend itself to the protection of steep abutments.

Overtopping protection for embankment dams utilizing conventional concrete relies on a continuous layer of concrete to serve as the flow surface for overtopping flows. This normally consists of a smooth, continuously-reinforced concrete slab (CRCS) constructed over a filtered drainage layer on the downstream face of the dam. The concrete slab and drainage layer protects the underlying embankment from high velocity flows discharging along the downstream face of the dam. Training walls are normally required at the sides to contain the overtopping flows and to protect the abutments. Defensive measures are required to prevent or minimize the passage of water through joints and cracks.

Conventional or mass concrete can be used to provide overtopping protection for concrete dams in the form of concrete overlays that protect the underlying rock foundation at the downstream toe of the dam and along the downstream abutments. The overlays protect the rock from overtopping flows that could pluck rock blocks from the foundation or scour and remove weaker material along shears or faults within the dam foundation. Splitter piers are often added to the concrete dam crest to aerate the overflow jet. An example of concrete overtopping protection is Coolidge Dam in Arizona (below).

Precast concrete systems – ACBs and tapered wedge blocks

Precast concrete blocks can be used on embankment dams to provide a hard surface for overtopping flows to pass safely without eroding the underlying surface, and are commonly referred to as articulating concrete blocks (ACBs) when used for this purpose. 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 "articulating" implies the ability of the matrix to conform to minor changes in the subgrade while remaining interlocked or interconnected using cables, pins, or anchors.

There are many types of precast concrete blocks used, including cable-tied, interlocking, and overlapping (or tapered wedge) blocks. Each has its own geometry, useful application based upon hydraulic performance and erosion prevention, installation procedures, aesthetic