The use of geomembranes for emergency spillways

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In September 1981, during an inspection programme of non-Federal dams in the USA, 3000 structures were identified as being unsafe, of which 81 per cent had problems relating to their spillway capacity. The author of this article describes the advantage of installing a membrane-lined emergency spillway as a lower cost alternative to conventional concrete-lined or rock-lined compacted earth spillways. Field studies carried out to study the behaviour of a flexible membrane for this application are described.

IN SEPTEMBER 1985, construction of an emergency spillway using geomembranes at Cottonwood dam No. 5 in the USA was finished. This was the completion of a major phase of a study by the Bureau of Reclamation on flexible membrane- or geomembrane- lined emergency spillways. The study has included a review of the problem, possible solutions, design of a field study, and construction of an operational spillway. It is planned that next spring the emergency spillway will be operated for a field test.

Growing concern over inadequate emergency spillway capacity for existing embankment dams has resulted in consideration of the use of flexible membrane-lined emergency spillways as a low-cost alternative. The membrane industry now offers a wide range of materials for consideration. It has begun the investigation on the use of membrane emergency spillways for low-head structures. With increased knowledge, consideration can be given to higher head structures. The field study involves an 80 m-long Hypalon lining on a spillway of the Cottonwood 5 earth dam located near Grand Junction, Colorado (Fig. 1). The structure is 137 m wide and 5.8 m high at el. 3050. A two-year study of the material used shows minimal change of important engineering properties. This was reported at the 1984 International Conference on Geomembranes.

The problem

On 30 September 1981, the Corps of Engineers discovered, during their inspection programme of non-Federal dams, that nearly 3000 dams were unsafe, requiring some remedial action. Of these, 81 per cent were deficient because their spillways were too small to pass the estimated maximum floods. This reflects the difference between present-day design flood criteria contained in the "Recommended Guidelines for the Safety Inspection of Dams" and the criteria in vogue at the time the dams were constructed[1,2,3].

Embankment dams are particularly sensitive to failure caused by overtopping, both during construction and while in service. However, inadequate spillway capacity is not the only cause of overtopping failure. There have also been many cases where dams were overtopped because of gate failure[4].

These potential hazards can be avoided by adding an emergency spillway with the required discharge capacity. However, in many cases, the cost for a conventional concrete-lined spillway or even a rock-lined compacted-earth spillway would be prohibitive.

Proposed solution

It was decided that an attractive approach would be to provide a membrane-lined emergency spillway. The flexible membrane would be covered with soil until the spillway was needed for operation. At the beginning of emergency spillway operation, the soil would be washed away, and the membrane lining would carry the flow, protecting the embankment from erosion[5].

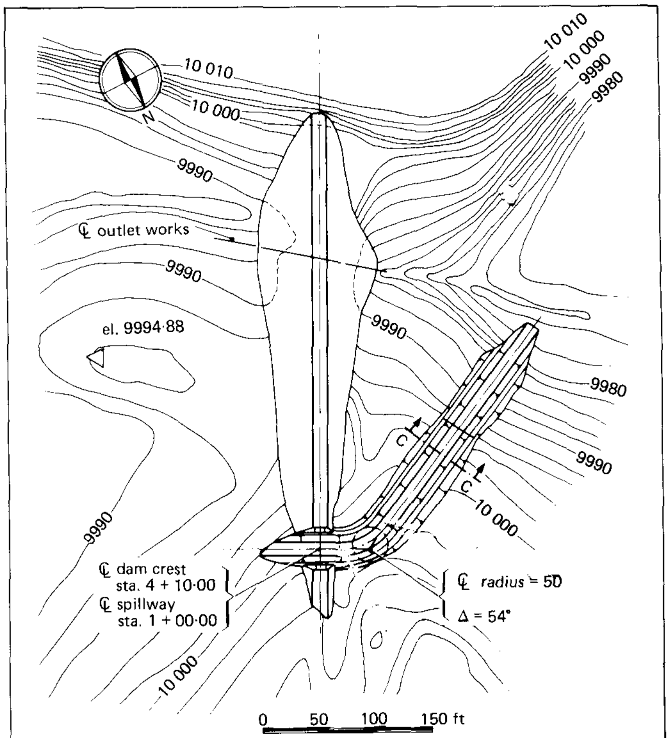

Fig. 1. Overall plan view of the Cottonwood No. 5 dam and emergency spillway.

The basic concept is that with both existing and new embankment dams, a low-cost spillway could be constructed on or adjacent to the embankment, consisting of a geomembrane-lined earth structure. The function of the membrane during operation is to provide a watertight barrier which protects the earth from erosion. To be successful, the geomembrane must be strong enough to resist damage from hydraulic forces and debris during operation. Further, it must have suitable chemical properties to have long-term durability. A soil cover would be provided to protect the geomembrane from accidental mechanical and animal damage. During operation, the soil cover would be washed downstream, exposing the geomembrane lining which would provide good hydraulic characteristics.

The geomembrane would be installed so that each sheet overlaps the adjacent downstream sheet by a few feet. The sheets would not be bonded to each other. This type of construction provides a positive seal for water flowing down its surface while providing relief for any hydrostatic pressures present under the lining. It also prevents the accumulated transfer of stress caused by dynamic loading of the operating spillway.

Significant advances have been made in recent years in the manufacture of flexible membrane materials that are suitable for a wide range of water resources engineering work, and

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many excellent materials are now available. Much work has been done to identify the important properties of these materials. Laboratory testing, field studies, and observations of these materials in place have provided guidance for the selection of durable materials[6, 7].

A search of the literature did not reveal reports on the use of flexible membranes for emergency or normal spillways of embankment dams. However, one report suggested that some encouraging work was being done in France, and another study from the USSR concluded that flexible or soft spillways should be studied further[8, 9].

Investigation

Because the use of a flexible membrane in a low-cost emergency spillway appeared to have merit, a study of modest scope was begun by Burec. The investigation started with an evaluation of the feasibility of various applications for low-head structures[10, 11]. Locations where the consequences of failure would not be serious were given primary consideration. A number of potential applications exist including low-head structures with inadequate spillways, new low-head earth dams, low-head dykes on large reservoirs, saddles suitable for emergency overflow where erosion could be a problem, and improvements to existing emergency/auxiliary spillways.

The primary objective of the research is to develop design procedures, materials specifications, construction procedures, and cost data to assist in the selection, design, and construction of geomembrane emergency/auxiliary spillways for low-head structures. Based on experience gained the potential for high-head structures can be evaluated.

Field study

The construction of a flexible membrane emergency spillway at Cottonwood dam No. 5 is an important part of the present study. This small earth dam, which is being rehabilitated, offered an excellent opportunity for the field study. There are two important characteristics of the structure that make consideration of a geomembrane-lined emergency spillway attractive for the first field installation. The spillway will operate only infrequently, and when it does, relatively small discharges are expected. Frequency of spillway use is important because of the maintenance effort required to replace the soil cover after each period of operation. The small upstream drainage area, of less than 1 sq mile (2.5 km^2), results in small spillway discharges, even for infrequent floods. Some of the questions that will be addressed in this study are summarised as follows.

- When membranes are used on slopes, what effect does drag caused by the water velocity component have on the membrane? How does drag affect the membrane's tensile properties at its support, and does it cause the uplift of the sheet from its foundation?
- What are the effects of abrasive sands and materials on the membrane?
- What are efficient methods of anchoring the membrane along the sides and in the transverse direction?
- What would be the minimum depth of cover material required to protect the membrane from the elements, and from accidental mechanical and animal damage, and what is the best type of cover material to use?
- Would erosion of the cover material during operation pose a serious problem for downstream hydraulic structures and machinery?
- What effect does high water velocity, 4-5 m/s, have on the membrane when the sheet is wrinkled after placement?
- Is special foundation treatment needed before the membrane is placed?
- What are the effects of aging on the durability and permeability of membranes?
- How is the membrane affected by different soil types and vegetation (root) growth?

Cottonwood dam No. 5 is one of 17 small private reservoirs of the Collbran project that were constructed on the Grand Mesa, near Grand Junction. These reservoirs, which are filled during the spring runoff, regulate the runoff from small streams. The stored water is released on demand for hydroelectric power and irrigation.

A Burec SEED (Safety Examination of Existing Dams) report recommended that Cottonwood dam No. 5 be breached and reconstructed. This recommendation provided the opportunity for the implementation of the flexible membrane emergency spillway study.

Design considerations

Spillway design considerations can be summarised as follows:

- The spillway is aligned to pass through the more plastic materials on the right abutment, to provide additional erosion protection if needed.
- Two grade sills are provided: one at the upstream end of the membrane liner to provide flow control and prevent piping, and the other at the downstream end to prevent head-cutting back into the spillway.
- The edges of the liner along the sides and the upstream edge of the transverse joints were placed in trenches, which were subsequently backfilled with compacted soil.
- Transverse joints between adjacent sheets were not bonded. This prevents stress buildup in one sheet from being transferred to another.
- Each sheet overlaps its adjacent downstream sheet by approximately 1.5 m to provide adequate protection of the compacted backfill which anchors the downstream sheet.
- A protective cover of 150 mm of non-cohesive material was provided over the flexible membrane to protect it from foot, animal, and vehicle traffic. Materials were dredged from Cottonwood Lake No. 1, which are non-cohesive and are expected to wash away during spillway operation.
- The alignment was chosen so that discharges will not occur along the toe of the dam.
- Inflow design flood is the 100-year flood. This results in a design discharge of 1.13 m^3/s.
- Flow passes through critical depth at the upstream grade sill; therefore, the flow is supercritical over all areas protected by the flexible membrane liner.
- The channel bottom width is 3.66 m with 2:1 side slopes and a depth of 0.91 m (to provide freeboard). This is based on the water surface profile in the spillway channel.
- The assumed Manning's number is $n = 0.025$ for the protective cover in place and $n = 0.015$ for the flexible membrane.
- The maximum channel velocity is 4.42 m/s.
- Energy dissipation is to be provided by a natural hydraulic jump, which should form over the downstream channel riprap protection.
- Riprap is sized to resist displacement caused by velocities associated with the design discharge.

The essential features of the installation are shown in Figs. 1-4. The desired physical properties of flexible membranes for applications in the emergency spillways include high tensile strength and flexibility, high puncture and abrasion resistance, good impact tear resistance, good weatherability, and immunity to bacterial and fungus attack.

At present, two types of lining materials that may be suitable for this application are the fabric-reinforced materials, such as Hypalon and c.p.e. (chlorinated polyethylene) and h.p.d.e. (high density polyethylene) materials. The cost range for these is from \$5 to \$10/m^2.

For a test at Cottonwood, field seaming would not be very practical because of the remote location of the dam. Therefore, only reinforced sheets were used, since they can be prefabricated for transport to the site unlike non-reinforced materials which have to be field seamed.

The material selected for the field study is 0.9 mm

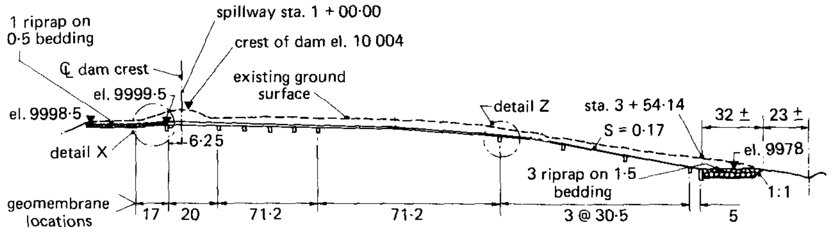


Fig. 2. Profile along the centreline of the spillway showing the location of the geomembrane blankets.

reinforced Hypalon sheet, fabricated to 11.6 by 12.2 m and 11.6 by 7.01 m[11].

A question has been raised about potential cavitation damage to the membrane during high velocity flow. Cavitation damage occurs downstream as a result of an abrupt change in surface condition, such as a seam or wrinkle in the membrane. The most severe condition is a right angle offset into the direction of flow. The criteria for incipient cavitation to begin is for the cavitation number

$$\sigma = 2(P_o - P_v/\varrho_{wv}{}^2)$$

where: Po = absolute pressure at the surface; Pv = vapour pressure of water; ϱ_{wv} = mass density of water; and v = water velocity.

For a right angle offset into the direction of flow, $\sigma = 1.9$. A safe criterion for no cavitation to occur, then, is $\sigma > 2$. This results in a requirement for a velocity greater than 8.2 m/s for cavitation to occur. The design velocity of 4.42 m/s is much lower than this value, hence, cavitation damage is not expected[12, 13].

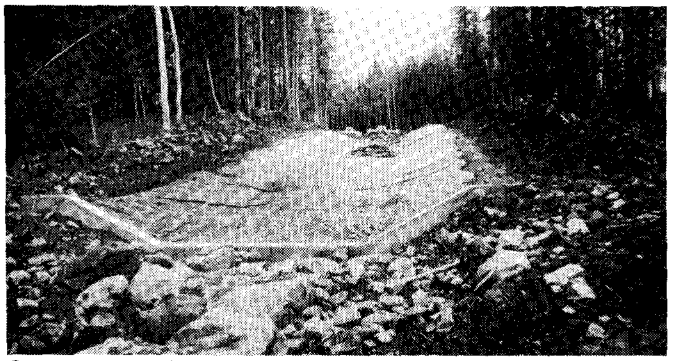
Study programme at Cottonwood

To obtain the maximum benefit from the field study, a two-part programme will be followed, comprising a short-term and a long-term phase. The short-term phase concentrates on design and construction factors and an initial assessment of the spillway operation. Long-term studies cover operation and maintenance and geomembrane serviceability.

Before construction, water emersion and outdoor exposure tests were conducted on samples of the membrane to be used in the field study. Although some properties underwent some changes, the changes were considered minimal. There was no indication of progressive deterioration with time, and the changes were consistent with those that occur with the cure of this material in the first few weeks of exposure[11].

Construction of the spillway was carried out by hand placement of eight geomembrane blankets approximately 12.5 m wide. The length ranged from 1.5 to 21.4 m as shown in Fig. 2. After the geomembrane blankets had been placed and the edges secured as shown in Figs. 3 and 4, the cover material was placed. The entire placement of the membrane and cover material was accomplished between June and September 1985. Because of the high altitude, remote location, and periods of bad weather, construction had to proceed a few days at a time, during periods of suitable weather.

Plans are being made for an operational test next spring. The outlet works will be blocked, and the emergency spillway will be operated. Field studies will cover:



Geomembrane placed at the lower end of the spillway.

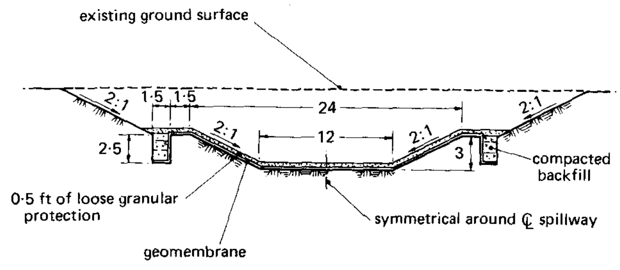


Fig. 3. Typical cross-section, showing the location of the geomembrane, the soil cover, and the extent of the sides of the geomembranes.

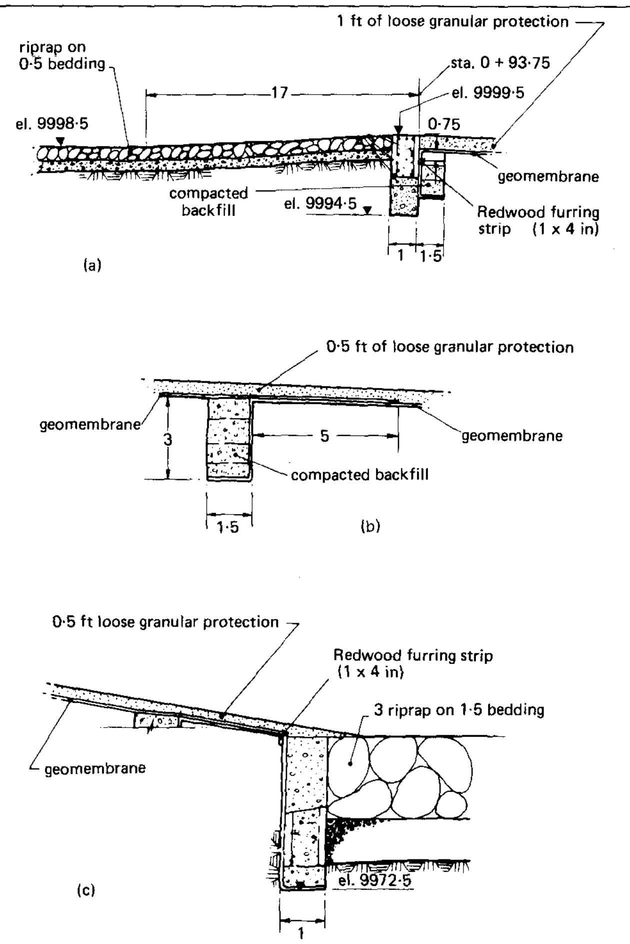


Fig. 4. Termination of the upstream and downstream ends of the geomembrane blankets, showing: (a) upstream end of the spillway at the dam crest; (b) typical section along the spillway showing an overlap of approximately 5 ft (1.5 m); and, (c) downstream end of the spillway.

- behaviour of the cover material;
- interaction of the cover material and the geomembrane;
- behaviour of the geomembrane; and,
- hydraulic characteristics of the geomembrane-lined spillway.

Long-term studies will follow this operational test, involving removal of test specimens of the geomembrane for durability studies and observations during subsequent service and operation of the spillway. □

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