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EMERGENCY SPILLWAYS USING GEOMEMBRANES

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16. ABSTRACT

A field study evaluated the design, construction, and operation of a low-cost auxiliary spillway consisting of an earth channel lined with a geomembrane (36-mil Hypalon) protected by an erodible earth cover. The study was conducted at Cottonwood Dam No. 5, Collbran Project, Colorado. The field test installation was completed in the fall of 1985, and an operational test was conducted in the summer of 1986.

During the field test, the spillway operated essentially as expected. The soil cover was washed away during the initial flows until the membrane on the bottom of the spillway was exposed. Even though the flow carried much abrasive material, stones, and a few cobbles approximately 100 millimeters in diameter, little or no erosion of the membrane was observed. The overlapped field joints of the membrane functioned well. Future designs should be improved by curved bottom cross sections rather than the usual flat bottom of a trapezoidal section. This would minimize the amount of cover washed away at low flows. The concept could be extended by providing vegetated earth cover that can handle lower floodflows and not require recovering the spillway.

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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INTRODUCTION

The use of flexible membrane lined emergency spillways is being shown to be a feasible solution to the problem of inadequate spillway capacity for some existing embankment dams. The USBR (Bureau of Reclamation) has completed the initial stage of an investigation on the use of membrane emergency spillways for low-head structures (<15 m). This study, initiated in 1981, involved the installation of an 80-meter-long flexible lining on a spillway of an earth dam located near Grand Junction, Colorado, at an elevation of 3050 meters. The field test installation was completed in the fall of 1985, and an operational test was conducted in the summer of 1986. Long-term studies on this installation are continuing. These studies involve the removal of test coupons of the flexible lining for durability studies and behavioral observations of the spillway both during and between the passage of flows throughout the research period.

SUMMARY

A field study evaluated the design, construction, and operation of a low-cost spillway consisting of an earth channel lined with a geomembrane protected by an erodible soil cover. The concept was tested on a 5.8-meter-high by 137-meter-wide dam in Colorado. In 1986, construction was completed and a field test performed to evaluate the behavior of the erodible soil cover and the operation of a geomembrane-lined channel. During the field test, the flow was about 0.7 m^3/s with a maximum velocity of 8 m/s.

In the field test, the spillway operated essentially as expected. During the initial flows over the spillway, the soil cover was washed away until the membrane on the bottom of the spillway was exposed. Even though the flow carried much abrasive material, stones, and a few cobbles approximately 100 millimeters in diameter, little or no erosion of the membrane was observed. The overlapped field joints of the membrane functioned well. Future designs should be improved by curved bottom cross sections rather than the usual flat bottom of a trapezoidal section. This would minimize the amount of cover washed away at low flows. The concept could be extended by providing vegetated earth cover that can handle lower floodflows and not require recovering the spillway.

Before construction, 2-year water immersion and outdoor exposure tests were conducted on samples of the membrane to be used in the field study. Although some properties changed, these changes were considered insignificant. This is because there was no indication of progressive deterioration with time and because the changes were consistent with those that occur with the Hypalon curing that takes place in the first few months of exposure.

BACKGROUND

In a 1981 survey of non-Federal dams, 81 percent had dam safety deficiencies because their spillways were not adequate to pass the estimated maximum floods. This reflects the difference between present-day design flood criteria and the criteria used when the dams were constructed [1, 2, 3]*.

Embankment dams are particularly sensitive to failure caused by overtopping, both during construction and while in service. There have also been many cases where dams were overtopped because of gate failure [4]. Because the cost of a conventional concrete-lined spillway or even a rock-lined compacted-earth spillway would be prohibitive for some reservoirs, an attractive approach would be to provide a geomembrane-lined emergency spillway. The geomembrane would be covered with a protective soil cover until the spillway is needed for operation. At the beginning of emergency spillway operation, the soil cover would be washed away, and the membrane lining would carry the flow, protecting the embankment from erosion [5]. 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. The function of the membrane during operation is to provide a watertight barrier that protects the embankment from erosion.

Narrow canyons present special problems for emergency spillways. If there is not an alternative valley available for an emergency discharge, the flow must be through the dam, over the dam, or tunneled around the dam through the abutment. With conventional engineering, any of these alternatives could encounter difficult engineering problems or extreme costs. For an embankment dam, a geomembrane-lined emergency spillway over the embankment may offer a cost-effective alternative to a conventional design. As with such spillways constructed in the adjoining abutment, the geomembrane would contain the flow and protect the embankment from erosion. A protective soil cover would be used to avoid mechanical damage when not in use and promote long-term durability. This potential use of geomembrane-lined spillways in narrow valleys is applicable both where the existing spillway is inadequate to convey the infrequent large floodflows or where an emergency spillway is required to supplement the operational spillway.

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* Numbers in brackets refer to entries in the bibliography.

INITIAL INVESTIGATION

The geomembrane must be strong enough to resist damage from hydraulic forces and debris during operation. It also must have chemical properties that provide very long-term durability. Significant advances have been made in recent years in the manufacture of flexible membrane materials suitable for a wide range of water resources engineering work. Extensive work has been performed to identify the important properties of the many excellent materials now available. Laboratory testing, field studies, and observations of these materials in place have provided guidance for the selection of durable materials [6, 7]. Encouraging studies have also been done in France and the U.S.S.R. [8, 9].

The USBR investigation included an evaluation of the feasibility of various applications for low-head structures [10, 11]. The initial potential applications include existing low-head structures that have inadequate spillways, new low-head earth dams, low-head dikes on large reservoirs, saddles suitable for emergency overflow where erosion could be a problem, and improvements to emergency/auxiliary spillways. In 1983, a geomembrane was installed as part of the emergency fuseplug spillway at the Lake Byllesby Dam in southern Minnesota [12].

Ultimately, the investigation is intended to produce 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. With the experience gained in studying low-head structures, the potential of geomembranes for high-head structures can be evaluated.

FIELD STUDY

The rehabilitation of Cottonwood Dam No. 5, Collbran Project, Colorado, offered an excellent opportunity for a field study. Some of the questions addressed in this study are:

1. When membranes are used on slopes, what effect does the water velocity have on the membrane? Does drag produce a tensile force on the membrane exceeding its strength? Does the flow uplift the sheet from its foundation?

2. What are the effects of abrasive sands and materials on the membrane?

3. What are efficient methods of anchoring the membrane along the sides and in the transverse direction?

4. What is the minimum depth of cover material required to protect the membrane from the elements and from accidental, mechanical, and animal damage. What is the best type of cover material to use?

5. Would erosion of the cover material during operation pose a serious problem for downstream hydraulic structures and machinery?

6. What affect does high water velocity (4 to 5 m/s) have on the membrane when the sheet is wrinkled after placement?

7. Are special foundation treatments needed before the membrane is placed?

8. What are the effects of aging on the durability and permeability of membranes?

Cottonwood Dam No. 5 is 1 of 17 small private reservoirs of the Collbran Project that was constructed on Grand Mesa, near Grand Junction, Colorado. These reservoirs, which are filled during the spring runoff, regulate the runoff from small streams. The stored water is released on demand for hydroelectic power and irrigation purposes.

A USBR 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

Cottonwood Dam No. 5 is an embankment dam 5.8 meters high and 137 meters wide. The geomembrane spillway was aligned through the more plastic materials on the right abutment to provide additional erosion protection if needed, as shown on figure 1. The geomembrane-lined channel is 80 meters long and 1 meter deep with a 3.6-meter bottom width, 2:1 side slopes, and a maximum slope of 0.170. Two grade sills are provided: one at the upstream end of the membrane liner to provide flow control and to prevent piping, the other at the downstream end to prevent head-cutting back into the spillway. In considering the spillway design, it was clear that the geomembrane should be installed so that each sheet overlaps the adjacent downstream sheet by 1.5 meters. The sheets should 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 under the lining. This type of construction also prevents the accumulated transfer of hydraulic sheer stress from sheet to sheet during operation of the spillway. Design details are shown on figures 2, 3, and 4.

The edges of the liner along the sides and the upstream edge of the transverse joints were placed in trenches that were subsequently backfilled with compacted soil. A protective cover of 150 millimeters of noncohesive material was placed over the flexible membrane to protect it from foot, animal, and vehicle traffic. Noncohesive soil materials were selected so that they would erode during spillway operation [10]. Gradation of the cover material is shown on figure 5.

With regard to spillway releases, the alignment was chosen so that discharges would not occur along the toe of the dam. Because the flow passes through critical depth at the upstream grade sill, the flow is supercritical over all areas protected by the flexible membrane liner. Energy dissipation was provided by a natural hydraulic jump, which forms over the downstream channel riprap protection. Riprap was sized to resist displacement caused by velocities associated with the design discharge.

It was considered that cavitation damage might occur downstream from 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. However, the design velocity, 4.42 m/s, is much lower than the minimum cavitation velocity. Hence, cavitation damage is not expected [11, 13, 14, 15].

Factors included in selection of the flexible membrane were high tensile strength and flexibility, high puncture and abrasion resistance, good impact tear resistance, good weatherability, and immunity to bacterial and fungus attack. Two types of lining materials that appear suitable for this application are the fabric-reinforced materials, such as Hypalon and CPE (chlorinated polyethylene) and HPDE (high-density polyethylene). Because of the remote location, small size, and onsite availability of some Hypalon, the material selected for the field study was 0.9-millimeter-thick reinforced Hypalon sheet, fabricated to 11.6 by 12.2 meters, and 11.6 by 7.0 meters [11] (table 1).

Table 1. – Material properties of Hypalon.

Property	Test method	Test value
Gauge (nominal)		36 mils (0.91 mm)
Piles reinforcing		1
Thickness (mm, minimum)	ASTM D 751	
1. Overall		0.86
2. Over scrim	Optical method	0.28
Breaking strength – fabric (kN, minimum)	ASTM D 751 method A	0.89
Tear strength (kN, minimum)	ASTM D 751 (modified)	
1. Initial		10.5
2. After aging		4.5
Low temperature (°C)	ASTM D 2136 3.2-mm mandrel, 4 hour pass	−40
Dimensional stability (each direction percent change maximum)	ASTM D 1204 100 °C, 1 hour	2
Volatile loss (percent loss maximum)	ASTM D 1203 method A, 0.36-mm sheet	0.5
Resistance to soil burial (percent change maximum in original values)	ASTM D 3083 0.36-mm sheet (modified)	0.5
a. Unsupported sheet		
1. Breaking strength		5
2. Elongation at break		20
3. Modulus at 100% elongation		20
b. Membrane fabric breaking strength	ASTM D 751 method A, procedure 1	0.11
Hydrostatic resistance (Mpa, minimum)	ASTM D 751 method A, procedure 1	1.72
Ply adhesion (each direction kN/m width, minimum)	ASTM D 413 machine method type A	1.75
Factory seam requirements		
Bonded seam strength – shear (factory seam, breaking factor, kN width)	ASTM D 751 (modified)	0.712
Peel adhesion (kN/m, minimum)	ASTM D 413 (modified)	Ply separation in plane of scrim or 1.75

OPERATIONAL TEST AT COTTONWOOD DAM NO. 5

To obtain the maximum benefit, the field test consists of a two-part program with both a short-term and a long-term phase. The short-term phase concentrates on design and construction factors and an initial assessment of the operation of the spillway. Long-term studies cover O&M (operation and maintenance) and geomembrane serviceability.

Construction of the spillway was begun by hand placing eight geomembrane blankets that were approximately 12.5 meters in width and ranged from 1.5 to 21.4 meters in length [15]. After placement, the upstream and side edges of the geomembrane blankets were secured in 1- by 0.5-meter trenches filled with compacted backfill. The protective cover of noncohesive soil was then placed on the blankets. 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 could be accomplished only a few days at a time during suitable weather conditions. Photographs taken during construction of the spillway are shown on figures 6 through 10. Figure 11 shows the completed spillway.

The operational test was conducted in July 1986. To provide the necessary reservoir level to conduct the test, the gate to the primary outlet structure was closed and flashboards were installed in a weir in the gate chamber that serves as a service spillway. For the emergency spillway, a total of 41 sandbags were stacked in 5 layers across the inlet channel, increasing the effective height of the reservoir above the emergency spillway crest by approximately 0.5 meters. A rope was attached to each sandbag and labeled so that the sandbags could be selectively removed during the test. Placement of the sandbags is shown on figures 12 and 13.

The operational test was conducted for approximately 3½ hours. At the beginning of the test, the reservoir level behind the sandbags in the emergency spillways was about 0.3 meters. During the test, the discharge was estimated to be 0.6 to 0.7 m^3/s, and the maximum velocity estimated to be 6 to 8 m/s. These velocities are higher than anticipated and may be attributed to a Manning's number that was lower than the assumed value of 0.015. Consequently, some additional studies should be conducted to obtain design data for establishing a Manning's number for spillways with flexible membrane linings.

The spillway operated essentially as expected, as shown on figures 14 through 18. Early in the operation of the spillway, the soil cover was washed away until the membrane on the bottom was exposed. From then on, gradual erosion of the cover on the sides of the spillway continued for a few centimeters up the sides. Even though the flow carried much abrasive material, stones, and a few cobbles approximately 100 millimeters in diameter, little or no erosion of the membrane was observed. Only one small tear, approximately 75 millimeters long, was found, (fig. 19); it was suspected that this occurred during construction. A fist-sized stone found under the membrane at this location was probably responsible for the tear. This tear was visible during the operation of the spillway but did not appear to increase in size.

The overlapped field joints of the membrane functioned well. Immediately after the test, the overlapped joints were inspected. The exposed portion of the geomembrane was wet from the flows; however, the portion under the overlap was completely dry (fig. 20). There was no evidence of accumulated tensile strain from one sheet to another. As expected, the membrane was installed with some wrinkles to help it conform to the subgrade. These wrinkles, did not cause any problems during the operation of the spillway.

Specific observations and results of the field test, in terms of the study objectives, are summarized:

1. The flow placed no noticeable serious strain on the geomembrane, and the overlapped joints helped avoid accumulation of tensile load along the spillway. Any uplift pressures were accommodated by the overlapped joints. The amount of uplift was minimal.

2. The geomembrane experienced little or no abrasive damage from the cover material as it was washed away.

3. The simple method of securing the membrane in 1- by 0.5-meter trenches filled with compacted soil was successful.

4. The soil cover proved successful in preventing mechanical damage to the geomembrane for the 10 months of exposure as a buried membrane lining. The cover was stable on the 2:1 side slopes.

5. As a precaution, the downstream hydroelectric facilities were protected from damage by the soil cover material by bypassing the turbid flow. However, this was necessary for only a few minutes as the stream quickly cleared up.

6. The velocity exceeded the expected 4 to 5 m/s and reached perhaps 6 to 8 m/s. Even at these higher velocities and with the wrinkled liner damage, distress, or cavitation was not observed.

7. Reasonable care must be taken to prepare the subgrade free of rocks and stones. If suitable material is not available for construction of the subgrade, a layer of fine-grained material will be needed under the geomembrane.

8. Aging and durability were not problems in the early field test, and none are expected because the normal early aging observed in the 2-year materials tests shows adequate retention of materials properties.

Future designs should be improved by curved bottom cross sections rather than the usual flat bottom of a trapezoidal section. This would minimize the amount of cover washed away at low flows. This concept could be expanded by providing vegetated earth cover that can handle floodflows with minimal erosion and not require recovering the spillway after each operation. Studies have recently been completed in England on the reinforcement of steep grassed waterways [16]. This may have application in USBR work, but would depend upon local soil and climatic conditions. To prevent the membrane from being torn by logs, trees, or branches, installation of a log boom upstream of the spillway should be considered.

LABORATORY TESTS

Water immersion and outdoor exposure tests were conducted on samples of the Hypalon liner installed in the spillway.

For water immersion, samples of the 36-mil lining material were placed in laboratory tapwater and tested after 4, 13, 26, 52, 78, and 105 weeks of immersion. The temperature of the running tapwater varied between 10 and 16 °C. The following ASTM tests were conducted on the samples after reconditioning at 23 °C and 50 percent relative humidity for a minimum of 40 hours:

No.	Test	ASTM Test Method
1	Thickness	D 751
2	Hydrostatic resistance	D 751, Method A, Procedure 1
3	Breaking strength	D 751, Grab Method A
4	Tear strength	D 751, Tongue Tear, Method B
5	Ply adhesion	D 431, Machine Method, Type A Specimens
6*	Bonded seam strength in shear	D 751, Grab Method A
7*	Bonded seam strength in peel	D 413

*Tests conducted on factory seams.

Samples were weighed before and after immersion to determine amount of water absorption. Samples of Hypalon were also placed in the E&R Center outdoor exposure test area and tested after 26, 52, 78, and 104 weeks of outdoor weathering; tests No. 1, 2, 5, and 7 were conducted on the samples.

Results for water immersion are summarized in table 2. Results show minimal changes in physical properties of the Hypalon, including three factory seams. There was some decrease in tear strength (from 162 to 116 lbf) after 105 weeks of immersion. The amount of water absorption was quite low: a weight gain of only 4.1% (surface dry condition) after 105 weeks of immersion. Outdoor exposure test results (see table 3) indicate, as with water immersion, little change occurred in the Hypalon physical properties.

Table 2. – Water immersion test results for 36-mil Hypalon. Sample No. B-7084.

Property test method	Original values	4-week Value	4-week % change	13-week Value	13-week % change	26-week Value	26-week % change	52-week Value	52-week % change	78-week Value	78-week % change	105-week Value	105-week % change
Weight gain, % (surface dry)	–	–	2.91	–	3.02	–	2.89	–	3.33	–	3.44	–	4.06
Weight gain, % (conditioned)	–	–	1.33	–	1.43	–	1.40	–	1.26	–	1.65	–	1.90
Thickness, mils, ASTM D 751	37.4	36.5	−2.4	36.5	−2.4	35.7	−4.5	34.6	−7.5	35.4	−5.3	34.9	−6.7
Hydrostatic resistance, lbf/in^2, ASTM D 751, Method A	420	421	0	399	−7.4	423	0.7	414	−1.4	413	−1.6	402	−4.3
Breaking strength, lbf, ASTM D 751, Grab Method A	254	198	−22.0	174	−31.5	188	−26.0	235	−7.5	273	7.5	274	7.9
Tear strength, lbf, ASTM D 751, Tongue Tear Method B	162	147	−9.3	122	−24.7	133	−17.9	144	−11.1	111	−31.5	116	−28.4
Ply adhesion, lbf/in, ASTM D 413, Machine Method Type A Specimens	7.2	6.7	−6.9	7.1	−1.4	6.1	−15.3	6.3	−12.5	6.8	−5.5	7.3	1.4
*Bonded seam strength in shear, lbf, ASTM D 751, Grab Method A	140	117	−16.4	112	−20.0	151	7.9	176	25.7	210	50.0	162	15.7
*Bonded seam strength in peel lbf/in, ASTM D 1876	23.0	15.1	−34.3	19.6	−14.8	–	–	23.5	2.2	23.9	3.9	24.5	6.5

* Tests conducted on factory seam.

Table 3. – Outdoor exposure test results for 36-mil Hypalon.

	Original values	26-week		52-week		78-week		104-week	
		Value	% change	Value	% change	Value	% change	Value	% change
Thickness, mils, ASTM D 751	37.4	35.6	−4.8	35.1	−6.1	35.2	−5.9	34.8	−7.0
Hydrostatic resistance, lbf/in², ASTM D 751, Method A	420	421	0	418	−0.5	414	−1.4	417	−0.7
Ply adhesion, lbf/in, ASTM D 413, Machine Method Type A Specimens	7.2	6.3	−12.5	5.4	−25.0	6.0	−16.7	6.4	−11.1
*Bonded seam strength in peel, lbf/in, ASTM D 1876	23.0	–	–	26.6	15.6	–	–	23.7	3.0

* Tests conducted on factory seams.

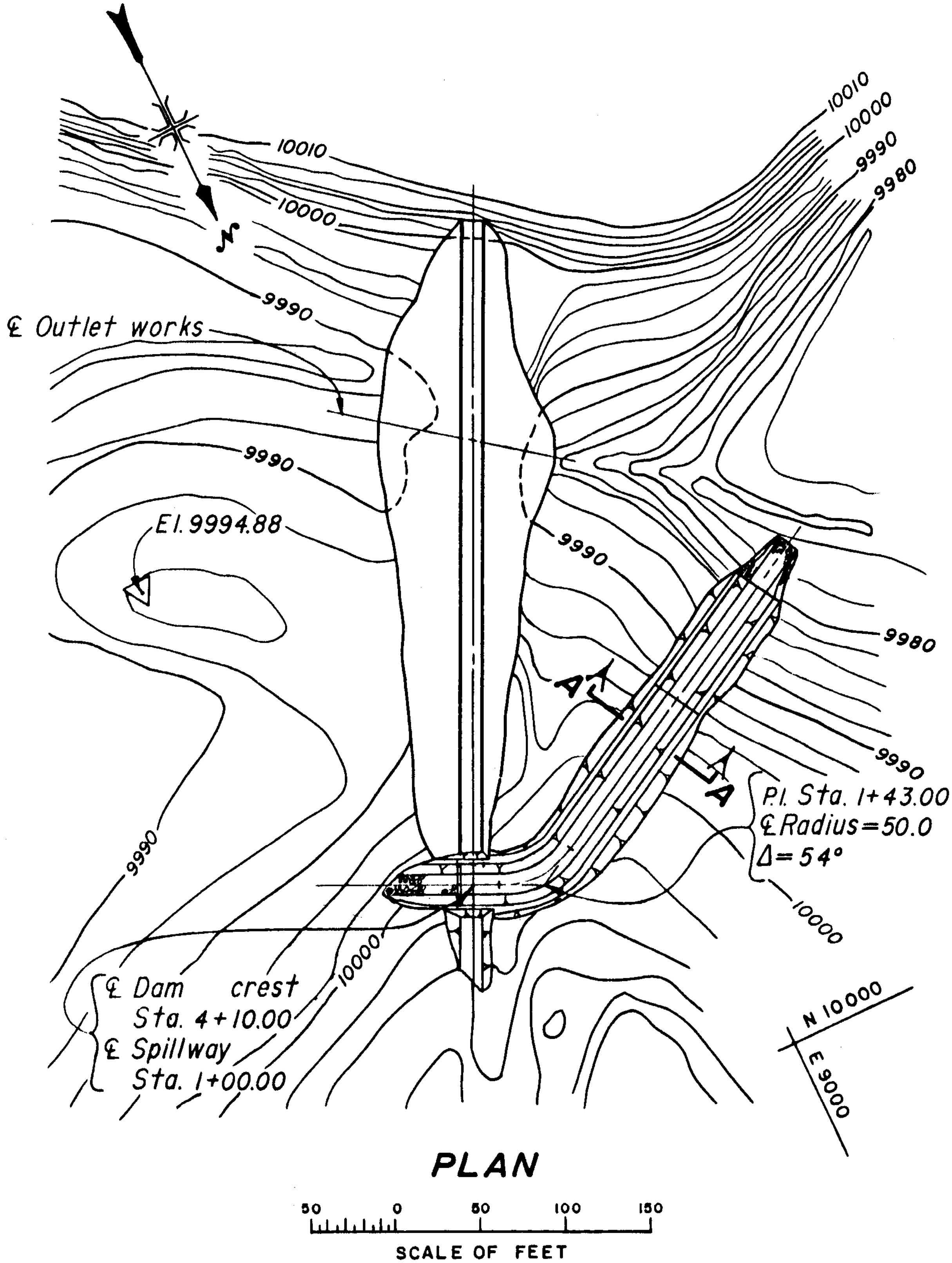


Figure 1. – Overall plan view of Cottonwood 5 Dam and emergency spillway.

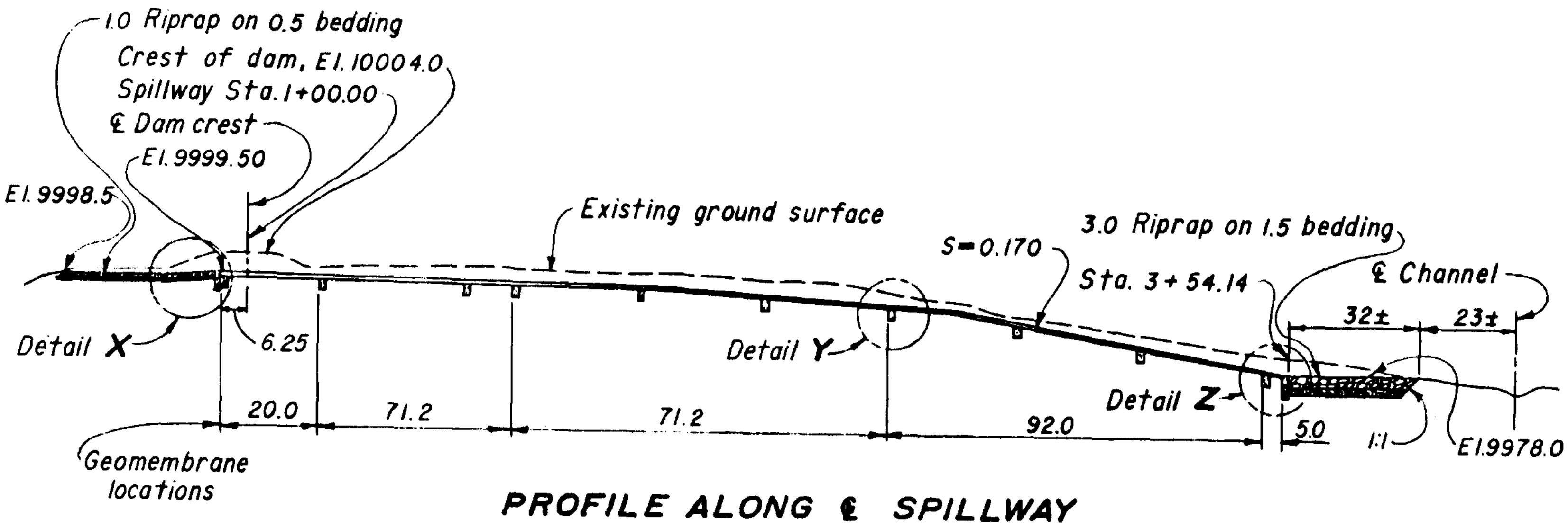


Figure 2. – Profile of the spillway showing locations of geomembrane blankets.

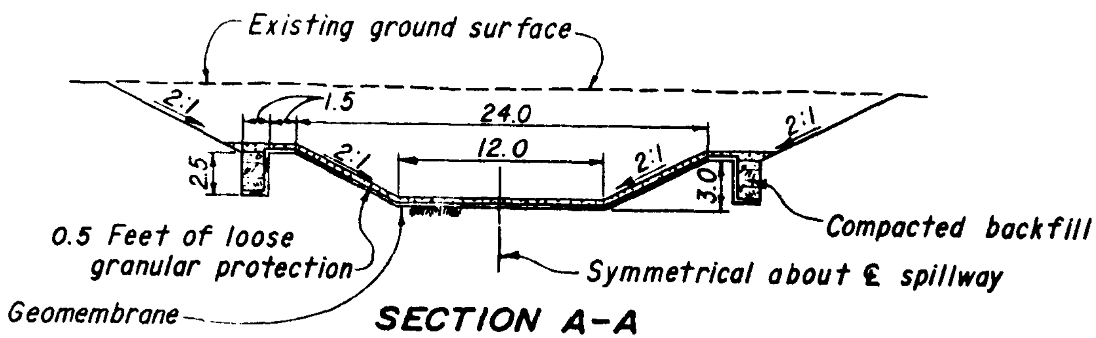
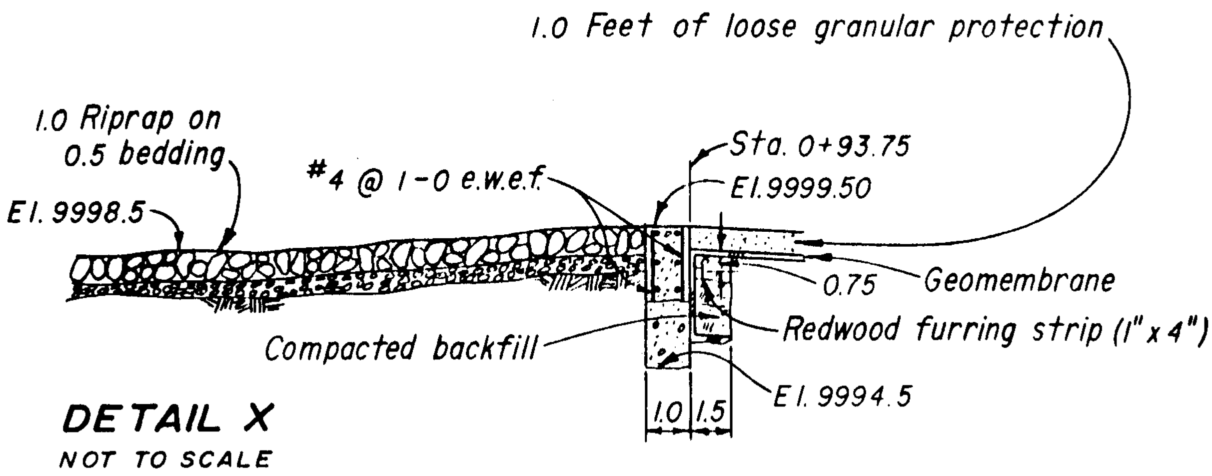
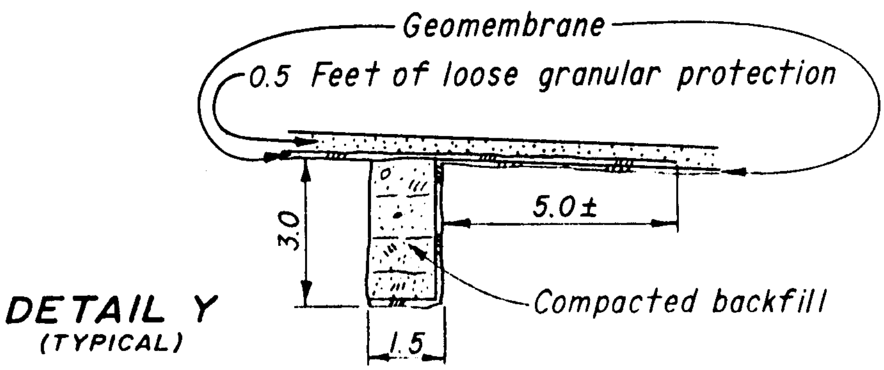


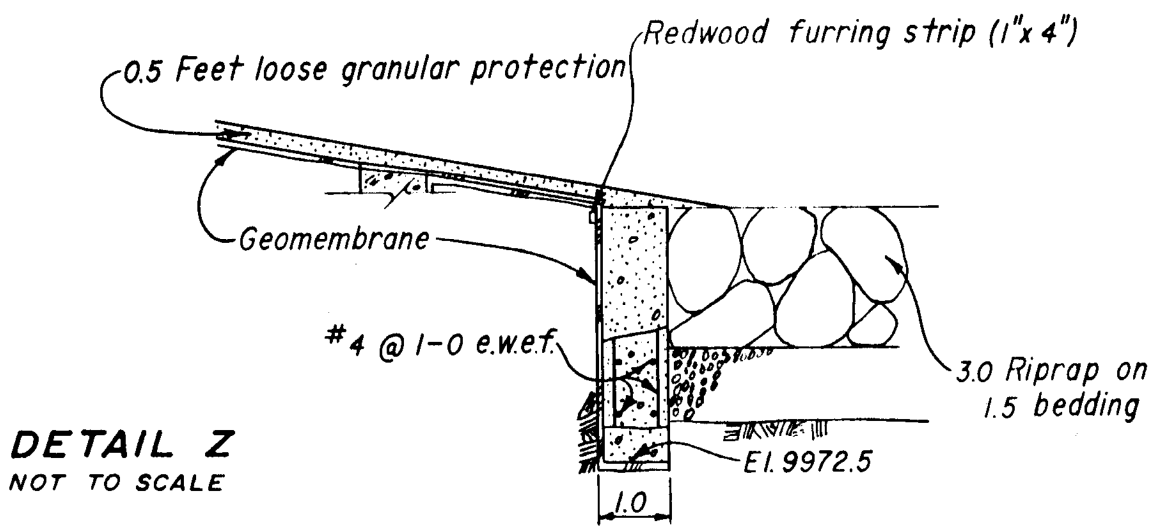
Figure 3. – Typical cross section of spillway. Location of the geomembrane, soil cover, and termination of the sides of the geomembrane.



(a) Upstream end of the spillway at the dam crest.



(b) Typical section along the spillway showing an overlap of approximately 5 feet.



(c) Downstream end of the spillway.

Figure 4. – Termination of the upstream and downstream ends of the geomembrane blankets.

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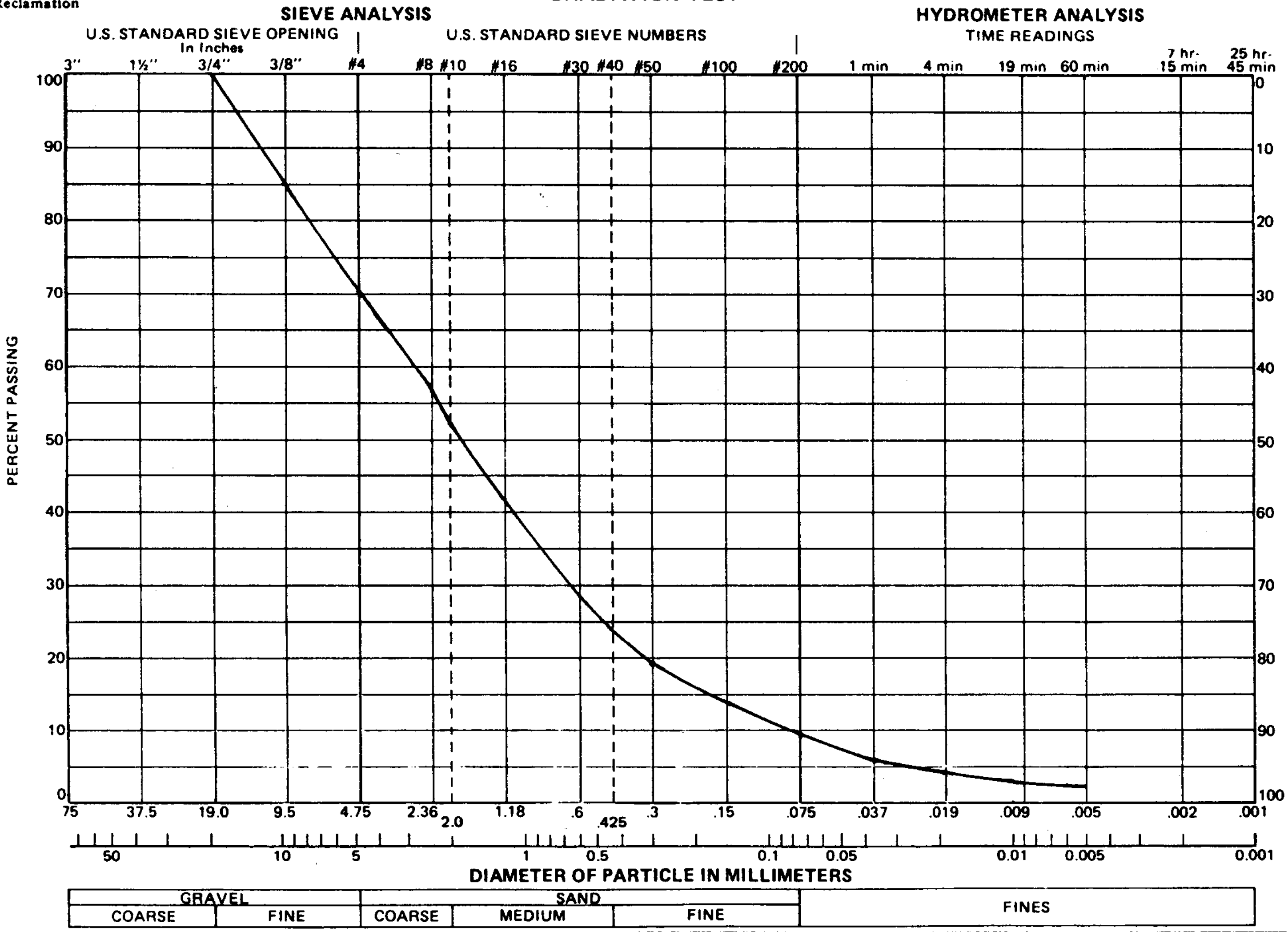
GRADATION TEST

Designation USBR ________ __ __



SAMPLE NO.	HOLE NO.	ELEV. OR DEPTH ☐ft ☐m	UNIFIED SOIL CLASSIFICATION GROUP SYMBOL	% GRAVEL	% SAND	% FINES	ATTERBERG LIMITS LL (%)	PI (%)	SL (%)	SPECIFIC GRAVITY MINUS NO. 4	OTHER	NOTES:
			SW-SM	30	61	9		NP		2.80		

Figure 5. – Gradation of soil cover.

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FIGURE 5

Figure 6. – Preparation of subgrade before geomembrane installation in spillway. P801-D-81368

Figure 7. – Section of geomembrane installed in spillway before backfilling and compacting anchor trenches. P801-D-81369

Figure 8. – Downstream end of geomembrane-lined spillway. Note concrete cutoff wall.
P801-D-81370

Figure 9. – Looking upstream at geomembrane-lined spillway. P801-D-81371

Figure 10. – Placement of soil cover to protect geomembrane from the elements and mechanical damage. P801-D-81372

Figure 11. – Completed spillway. P801-D-81373

Figure 12. – Placement of sandbags in spillway crest to form an artificial barrier. This barrier will be used to raise the reservoir level for the operational test. P801-D-81374

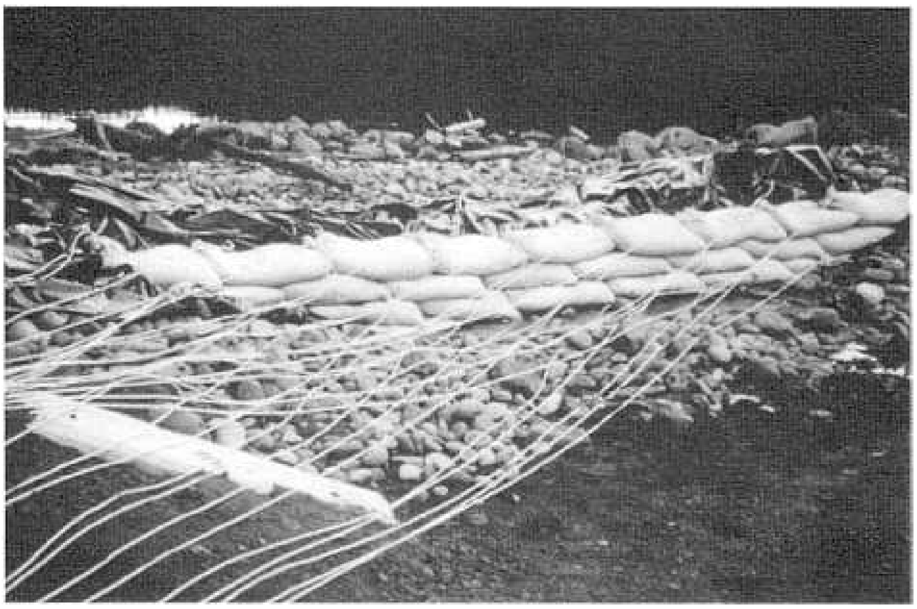

Figure 13. – Sandbags in place. A total of 41 sandbags were stacked in 5 layers increasing the effective height of the spillway crest by approximately 20 inches. P801-D-81375

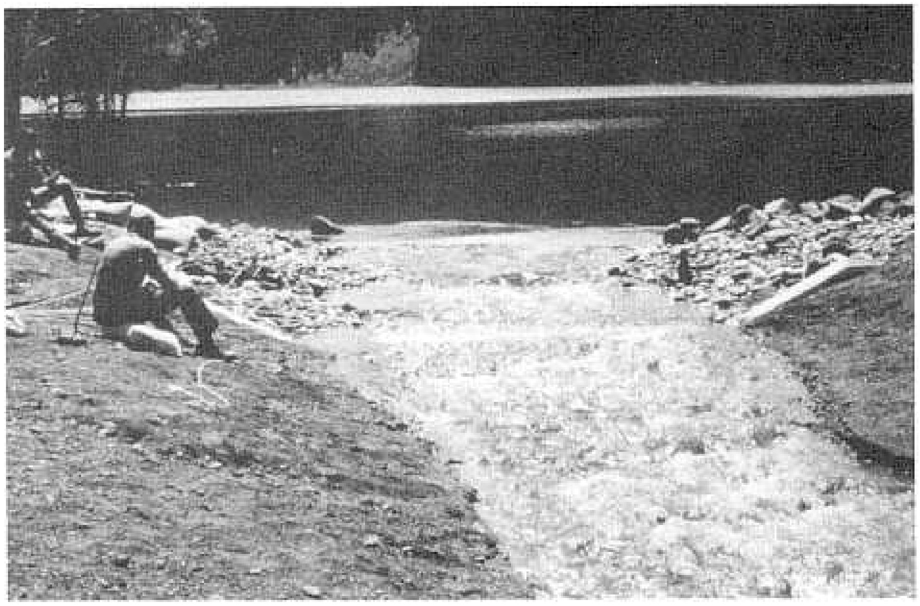

Figure 14. – Flow over spillway crest during operational test. The flow was estimated to be 0.6 to 0.7 m^3/s at a maximum velocity of 6 to 8 m/s. P801-D-81376

Figure 15. – Flow at downstream end of spillway. P801-D-81377

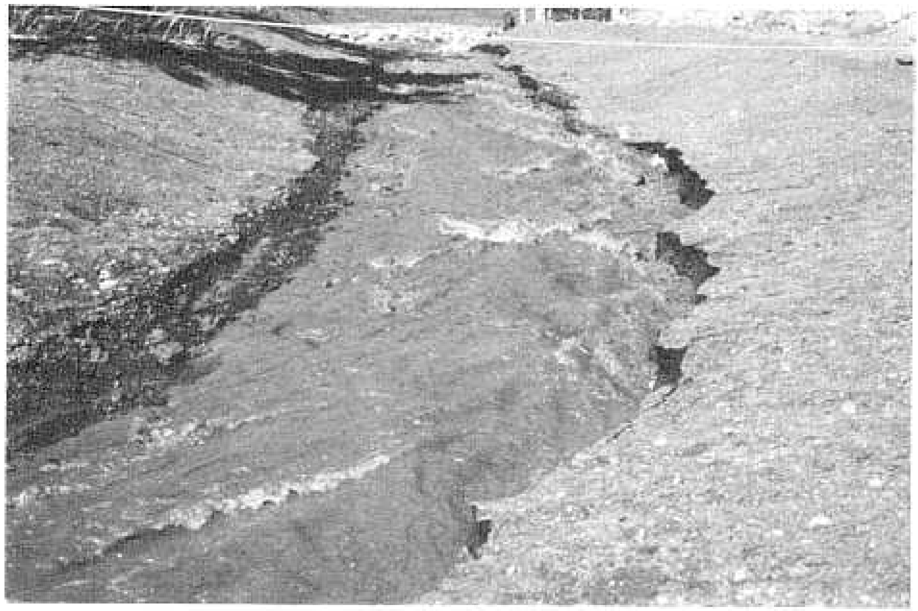

Figure 16. – Spillway during operation. P801-D-81378

Figure 17. – Looking upstream at geomembrane-lined spillway after operational test. P801-D-81379

Figure 18. – Downstream end of geomembrane-lined spillway after operational test. P801-D-81380

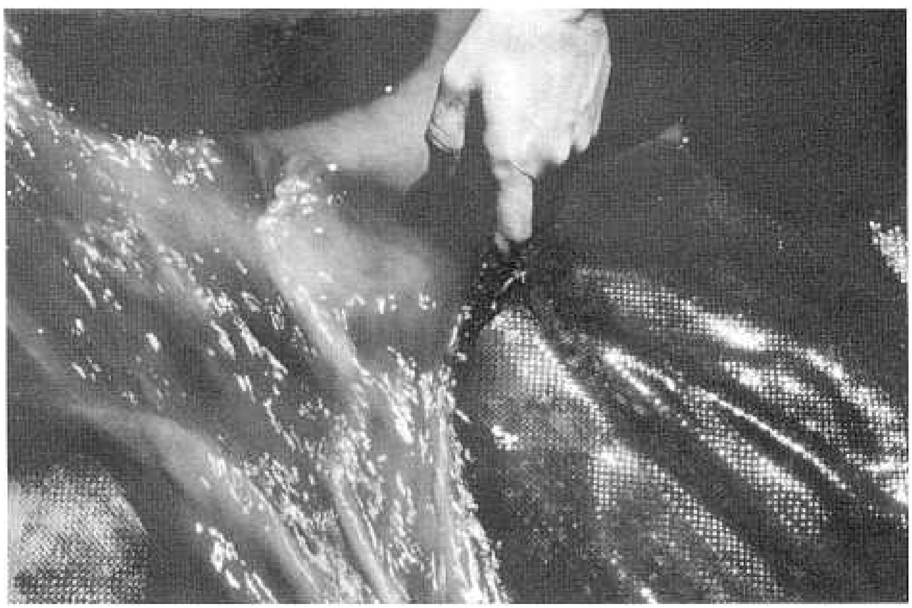

Figure 19. – Tear in geomembrane. This tear may have occurred during the original installation. The material was in excellent condition after the operational test with only several small areas exhibiting some abrasion damage. P801-D-81381

Figure 20. – Overlap seam after operational test. The geomembrane below the overlap was dry. P801-D-81382

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