CANAL LININGS USED BY THE BUREAU OF RECLAMATION WITH EMPHASIS ON REHABILITATION

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ABSTRACT

Designers, and others interested in water resource development, have strived to improve the cost effectiveness and technical properties of canal liners. Reclamation (the Bureau of Reclamation) has been involved in this endeavor for many years. Although the majority of Reclamation canals have been successfully lined with either concrete or compacted earth, a need was recognized for the development of alternative linings, along with the improvement of linings already in use. This paper will present a brief history of canal linings tested and used by Reclamation in the past and those currently under investigation, with an emphasis on linings which may be used for rehabilitations. The types of linings discussed include standard concrete, concrete placed underwater, shotcrete, compacted earth lining, compacted lime treated earth lining, soil-cement, buried geomembranes, exposed geomembranes, and geocomposites.

INTRODUCTION

It is the policy of Reclamation to line open channels when required to conserve water and secure other benefits. There are many factors that influence the type of lining chosen, and no single lining type can be recommended to satisfy all situations. Information on Reclamation lining criteria and practices appears in a variety of publications and papers, including the discontinued publication entitled "Linings for Irrigation Canals" [6]. While much of the information in this publication is still applicable, the publication was discontinued because there are areas where technological updates are required. A paper entitled "Interim Report On Canal Linings Used By The Bureau Of Reclamation" [4] will replace the above publication until it is updated. In addition to the above publication, information related to canal linings may be found in "Design

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Standards No. 3" [1], "Performance of Plastic Canal Linings" [7], and "Performance of Granular Soil Covers on Canals" [5].

HISTORY

From 1946 to 1962, Reclamation was involved in a lower cost canal lining study program, which culminated in the aforementioned publication, "Linings for Irrigation Canals". During the 16 years of study, 2,570 miles of lower cost linings and 420 miles of reinforced concrete linings were installed on Reclamation canals. The lower cost linings included unreinforced concrete, shotcrete, soil cement, asphaltic concrete, exposed asphaltic membranes, exposed plastic and synthetic rubber films, prefabricated concrete blocks, prefabricated buried asphaltic membranes, buried plastic and synthetic rubber films, bentonite membranes, thick compacted earth lining, thin compacted earth lining, and loosely placed (uncompacted) earth blankets.

Approximately 6,600 miles of canals have been constructed by Reclamation since the early 1900's. The "Linings for Irrigation Canals" document compared lining types for 2,993.8 miles of canals built between 1946 and 1962. It is estimated that approximately 1,400 miles of canals were constructed between 1962 and 1986. Table 2 shows, by percentage, an estimate

Table 1 - Percentages of types of linings on Reclamation-constructed canals

TYPE OF LINING	FROM 1963 PUBLICATION (3,000 MILES)	1963 TO 1992 (1,470 MILES)	TOTAL USBR CANALS (6,770 MILES)
Concrete	56%	55%	57%
Buried membrane			
Hot asphalt	11%	---	5%
Plastic	0.00004%	8 %	2%
Other	0.007%	---	---
Compacted earth	19%	37%	28%
Other	14%	---	8%

of the types of linings used on canals constructed during these two periods and also for all Bureau of Reclamation canals constructed since its inception in the early 1900's.

Table 1 clearly shows that unreinforced concrete lining has been the dominate lining used by Reclamation, for the construction of new canals, followed by compacted earth lining. Although geomembranes do not make up a large percentage of lining used by Reclamation, their use has increased dramatically in recent years.

BASIC LINING TYPES

Compacted Earth Lining

The lining of choice is a compacted earth of gravel and sand with clay binders or poorly graded gravel-sand-clay mixtures with a minimum thickness of 2 feet normal to the finished canal prism, if available within an economical haul distance. If properly maintained, this lining provides excellent seepage control (approximately 0.07 ft^3/ft^2 of prism/day) and excellent erosion protection. Table 2 shows the ranking of various earth materials (1 being best) with respect to use as compacted earth linings.

On the positive side, compacted earth linings can withstand colder temperatures with less damage than concrete lining; have a greater ability to tolerate frost heave, although a reduction in unit weight will usually occur due to frost action; can tolerate greater water surface fluctuations with less damage than can concrete or buried geomembrane lining; generally do not require as much foundation preparation as concrete or buried geomembrane linings; can tolerate certain expansive materials near the prism; and require no special equipment or technology for construction, which usually results in competitive pricing.

Negative attributes of compacted earth lining are the larger prism size and lower velocity required; potential erosion problems with borderline lining materials; and the care required to protect the integrity of the lining when cleaning the canal.

The following criteria are minimal guidelines for the layout and design of compacted earth linings and should be tempered with engineering judgment

Table 2 - Suitability of different soils for compacted earth lining

TYPICAL NAMES OF SOIL GROUPS	GROUP SYMBOLS	RANKING FOR EROSION	RANKING FOR LINING
Well-graded gravels, gravel-sand mixtures, little or no fines	GW	2	-
Poorly graded gravels, gravel-sand mixtures, little or no fines	GP	3	-
Silty gravels, poorly graded graded gravel-sand-silt mixtures	GM	5	6
Clayey gravels, poorly graded gravel-sand-clay mixtures	GC	4	2
Gravel with sand-clay binder	GW-GC	1	1
Well graded sands, gravely sands, little or no fines	SW	8	-
Poorly graded sands gravelly sands, little or no fines	SP	9[1]	-
Silty sands, poorly graded sand-clay mixture	SC	10[1]	7[2]
Sand with clay binder	SW-SC	6	3
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	ML	-	8[2]
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	CL	11	5
Organic silts and organic silt-clays of low plasticity	OL	-	9[2]
Inorganic silt, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH	-	-
Inorganic claus of high plasticity, fat clay	CH	12	10[3]
Organic clays of medium to high plasticity	OH	-	-

[1] If on the coArse end of gradation.
[2] Erosion critical.
[3] Volume change critical.

Table 3 gives the compacted earth lining thicknesses, in feet, for various rangeS of water depths. Table 4 gives the the freeboard above the normal water surface for the top of the lining and top of the bank. Table 5 gives the minimum b (bottom width) to d (water depth) ratios for various capacity ranges.

Table 3 - Thickness of compacted earth lining

WATER DEPTH (feet)	BOTTOM (Vertical) (feet)	SIDE (Horizontal) (feet)
2.0 or less	1.0	3.0
2.0 to 4.0	1.5	4.0
4.0 to 6.0	2.0	6.0
6.0 to 20.0	2.0	8.0
20.0 or more	3.0	8.0

Table 4 - Freeboard above normal water surface

CAPACITY RANGE ft^3/s	EARTH LINING (feet)	CONCRETE LINING (feet)	BANK HEIGHT (feet)
0 to 40	0.5	0.5	1.1 - 1.25
40 to 200	0.5	0.5 - 0.86	1.25 - 2.4
200 to 500	0.5 - 0.75	0.86 - 1.25	2.4 - 3.0
500 to 1,500	0.75 - 1.15	1.25 - 1.8	3.0 - 3.9
1,500 to 3,500	1.15 - 1.45	1.8 - 2.2	3.9 - 4.6
3,500 to 7,500	1.45 - 1.75	2.2 - 2.6	4.6 - 5.2
7,500 to 10,000	1.75 - 2.1	2.6 - 3.1	5.2 - 6.2

Table 5 - Minimum bottom width, b, to water depth, d, ratios

CAPACITY RANGE ft^3/s	EARTH	CONCRETE
0.25 - 25	2.0	1.0
25 - 100	2.0	1.2
100 - 500	2.5	1.2
500 - 1,000	3.0	1.3
1,000 - 2,500	3.5	1.3
2,500 - 5,000	4.0	1.5
5,000 - 7,500	5.0	1.8
7,500 - 10,000	6.0	2.0
10,000 - 15,000	7.0	2.5
15,000 - 20,000	8.0	3.0

The plasticity index, PI, should be greater than 12, the liquid limit, LL, should be less than 45, and the tractive force, TF, should be less than 0.65. The Mannings "n" is 0.025 for capacities less than 100 ft^3/s and 0.0225 for capacities greater than 100 ft^3/s.

Concrete Lining

The greatest percentage of Reclamation lined canals have concrete lining. Economics was usually the detrmining factor, but concrete linings were also used for mandated situations and technical reasons.

On the positive side, concrete linings have better hydraulic characteristics, including steeper side slopes (usually 1-1/2:1), resulting in a smaller canal prism; provide a seepage rate comparable to compacted earth lining (approximately 0.07 ft^3/ft^2 of prism/day), if properly designed, constructed, and maintained); present a hard, impenetrable barrier against burrowing animals; and significantly reduce weed growth in the canal prism. Finally, from a safety standpoint, reinforced concrete panels with water stop joints may provide the required structural capability and seepage control in critical areas where a canal bank failure could result in loss of life and/or damage to improvements, such as farm and residential structures, railroads, highways, etc..

Negative attributes are the extensive foundation treatment required for low density or highly expansive material; extensive and expensive underdrainage system required, when high groundwater is present; potential damage if the foundation is a frost susceptible soil; and the greater hazard potential to humans and animals because of higher velocities and steeper hard surfaced side slopes.

The following criteria are minimal guidelines for the layout and design of unreinforced concrete lining and should be tempered with engineering judgement. Table 4 gives the freeboard above the normal water surface for the top of the lining and top of the bank. Table 5 gives the minimum b (bottom width) to d (water depth) ratios for various capacity ranges. Table 6 gives the concrete lining thicknesses and contraction joint spacing for various capacity ranges. The canal bottom grade, s, must be less than 0.3 times the crital energy slope, s_c. Mannings "n" is 0.014 for a hydraulic radius, r, of 4 or less, and may be determined by:

$$n = 0.0463r^{1/6}/\log[14.8(r/0.005)]$$

when r is greater than 4.

Table 6 - Guidelines for the design of unreinforced concrete lining

CAPACITY RANGE (ft^3/s)	LINING THICKNESS (inches)	CONTRACTION JOINT SPACING (feet)
0 - 500	2-1/2	10
500 - 1,500	3	12
1,500 - 3,500	3-1/2	14
3,500 - 7,500	4	15
7,500 - 20,000	4-1/2	15

Membrane Lining

Tests on various membranes date back to the 1950's. Most of the test membranes in this era were asphalt based. Although test results on these membranes were encouraging technically, some membranes were labor intensive to install. Increased prices related to oil shortages in the 1970's made asphalt membranes uneconomical, and investigations were suspended. However, the use of buried PVC lining gained in popularity a few years later when better quality control and manufacturing techniques provided for higher quality and heavier plastic sheets at a competitive price. The majority of buried geomembrane used by Reclamation to date is 10 and 20 mil PVC.

Positive attributes are that a buried geomembrane may be placed during colder periods of weather; is especially adaptable for rehabilitating existing earth canals; is the type of lining least affected by frost heave or expansive material in the proximity of the canal prism; can tolerate greater water depth fluctuations than any other types of lining, if the cover material over the plastic is specifically designed to accommodate this condition; and provides a seepage rate equal to or less than that for concrete or compacted earth.

Negative attributes of a buried geomembrane are that the subgrade must be relatively smooth and free of sharp rocks, roots or other objects which may puncture the membrane; a side slope of 2-1/2:1 is usually required for stability of the cover material; the cover material, which requires a specific gradation, must be available from a local source to be economically feasible; an approved soil sterilant is required on the subgrade prior to placing PVC if weed growth is anticipated; and it is difficult to determine the location of damage once the cover material has been placed.

The following criteria are minimal guidelines for the layout and design of buried geomembrane linings and should be tempered with engineering judgement. The velocity range is from 1 to 3 ft/s, depending on the quality of cover material. Mannings "n" for earth canals is usually 0.025 for capacities less than 100 ft^3/s and 0.0225 for greater capacities. If the cover material is coarse, then Mannings "n" should be checked by the Strickler equation to determine if it should be increased. The Strickler equation is:

$$n = 0.0342\ d_{50}^{1/6}$$

where d_{50} is the diameter of the particle, in feet, for which 50 percent of the material, by weight, is smaller. The thickness of the cover material is calculated by:

$$c = 10 + d/12$$

where c is the cover material thickness, in inches (12-inch minimum), and d is the water depth in inches. Additional criteria are discussed under "Buried Geomembrane Rehabilitation" later in this paper.

REHABILITATION SITUATIONS

The most common reasons for rehabilitation are general deterioration of the lining or the addition of lining in canals that were initially constructed without lining. Other reasons for rehabilitation include problems with highly expansive foundation material, low density foundation material, soils susceptible to frost heave, and hydrostatic back pressure.

General Deterioration and Lining of Unlined Canals

Hundreds of miles of canals built in the early 1900's have experienced excessive deterioration, and canals that were initially constructed without any lining now require lining. Recent rehabilitations have favored geomembranes, but compacted earth and concrete have been used in specific cases.

<u>Compacted Earth Lining Rehabilitation:</u> If acceptable earth lining material is available near an existing canal requiring a new lining, a compacted earth will probably be the most economical lining. This was the option chosen to line portions of the Montezuma Valley Irrigation Company Lone Pine and Upper Hermana Laterals, located in southwestern Colorado, as part of the Colorado River Salinity Control Program.

<u>Concrete Lining Rehabilitation:</u> Concrete lining is usually used to rehabilitate old concrete-lined canals, especially if the major in-line structures are still in good condition, because of right-of-way, structural, and hydraulic gradient restrictions. Concrete lining may also be used to rehabilitate old earth canals, especially in an urban setting where right-of-way is restricted. This was true for a portion of the Government Highline Canal that passed through Grand Junction, Colorado.

<u>Buried Geomembrane Rehabilitation:</u> Buried PVC was installed in test sections on the Tucumcari Project in New Mexico and the Kennewick Irrigation district in Washington, and was used to rehabilitate portions of canals on the Helena Valley Unit in Montana, the East Bench Unit in Montana, the Riverton Unit in Wyoming, and the Government Highline Canal near Grand Junction, Colorado. Installations included both 10 and 20-mil sheets. Evaluations of buried membrane linings resulted in the following conclusions:

a. The thickness of the PVC should be a minimum of 20-mils (30 mils if heat seams are required). The 20 mil thickness provides more toughness and laboratory tests show that there is less aging (loss of plasticizers) with the thicker sheets. Aging increases tensile strength, decreases elongation properties, and decreases impact resistance. Test results also indicate that there is less aging with smooth subgrades.

b. The optimum side slope is 2-1/2:1 for stability of the cover material, unless the highest grade cover material is available. Cover material should fall between the gradation limits shown in Table 7, with the coarser limits more desirable.

c. The PVC should be covered immediately after installation with the surface temperature of the sheet between 35 and 90 degrees F, unless tests show there is no damage outside these temperatures.

d. If there were extensive vegetation in an existing canal that is to be rehabilitated with PVC, the foundation should be treated with an approved soil sterilant. Woody growth should not be allowed to take hold in the rehabilitated prism or on the bank near the top of the plastic sheet.

Table 7. Gradation for PVC lining cover material

Seive Size	Percent Retained Upper Limit	Percent Retained Lower Limit
5 inch	0	-
3 inch	20	0
1-1/2 inch	-	10
3/4 inch	80	-
3/8 inch	90	-
#4	-	50
#8	100	60
#30		77
#200		90

Other buried geomembranes tested include very low density polyethylene (VLDPE) and a polyolefin composite lining, both placed in the Belle Fourche Unit in South Dakota. The VLDPE sheet was 30 mils, and tests after 2 years showed no deterioration, but tests just recently taken indicate possible problems, and it is recommended that this material be used with caution until further studies can be completed.

The polyolefin composite consists of 3.5-oz/yd^2 needle-punched nonwoven polypropylene geotextile laminated to both sides of a 2- to 3-mil thick low density polyethylene (LDPE) sheet. The geotextile gives the composite strength and a texture to eliminate the sloughing of the cover material. The side slopes in the test section are 1-1/2:1, and the cover material has remained stable. This test is only 3 years old, and since preliminary tests on this and other "geocomposites" indicates that the geotextile and geomembrane may delaminate with freeze-thaw and/or wet-dry cycles, additional evaluations should be conducted before these materials are used extensively. Other "texturized" geomembranes should be considered in future evaluations.

A special case of buried geomembrane is bottom lining only in loessial soils. Because the permeability of loess is basically vertical, the seepage can be reduced from 50 to 60 percent by bottom lining only. This system has been successfully used on canals in Nebraska.

Exposed Geomembrane Rehabilitation: A variety of geomembranes have been considered for use as exposed liners for canals, some of which have been used as pond liners. Exposed geomembranes require gravel cover in the invert to help anchor the lining when the canal is empty. Potential advantages of exposed geomembrane linings are 1-1/2:1 side slopes, elimination of cover material on side slopes, easily identifiable damage, and more easily replaced damaged lining. Potential disadvantages are cost of the geomembrane, adverse wind and water forces, possibility of vandalism and animal damage, minor ultraviolet degradation, and abrasion.

A test section of 30-mil HDPE was installed on the Bostwick Division in Kansas. The material is in good condition except for a few small holes believed to be caused by deer. In addition, an exposed lining of VLDPE has been installed on the same canal, but future use of this material should be minimized until further evaluation is accomplished as previously stated.

Approximately 3 miles of a reinforced rubberized bituminous geomembrane was installed by the Kennewick Irrigation District in Washington in 1987 and tests in 1992 indicate that the material has experienced some delamination. Further studies are under way to detrmine if this is typical of this material or if a change in the formulation of this material will make it an acceptable alternative.

Underwater Lining of Existing Canals: There are many canals that require new lining for seepage control but cannot be taken out of service because they require year round operation. To solve this problem, Reclamation developed a system for underwater placement of a geomembrane lining with a protective concrete cover. A demonstration section of this lining system was placed on the Coachella Canal near Niland, California. A trimming machine was developed to shape the prism underwater. A special lining machine followed which placed the geomembrane (30-mil PVC on the invert and 3.4-oz/yd^2 nonwoven geotextile bonded to 20-mil PVC on the 2-1/2:1 side slopes) followed by the concrete protective cover. More detailed information can be found in "In-service Lining of Existing Canals" [3].

Concrete/shotcrete on Geocomposites: In addition to the underwater lining, studies have been made on the placement of concrete or shotcrete on geocomposites. Reclamation performed laboratory tests on placement of shotcrete on a geocomposite, although no field applications have been made to date. A short reach (1-1/2 mile±) of the Coachella Canal, in California, was constructed of hand placed concrete lining on a geocomposite of nonwoven geotextile glued to a PVC geomembrane.

Highly Expansive Foundation Material

If highly expansive material is used as a canal foundation or as compacted earth lining there is a very good chance that rehabilitation will be required. If acceptable material is available, the expansive material should be removed and replaced. If acceptable material is not available, lime treatment may be an acceptable alternative.

Reclamation's Friant-Kern Canal, located near Fresno, California, has extensive reaches of earth and concrete-lined sections situated in extremely fat clay. The side slopes of the earth and concrete-lined sections, and even 3:1 test sections, slumped into the canal when the soil became saturated. The canal lining was rehabilitated with lime treatment because there was no other acceptable material available. Hydrated lime or granular quicklime was added at the rate of 4 percent by the dry weight of the soil and thoroughly mixed until 100 percent would pass the 1-3/4-inch screen and 60 percent would pass the #4 screen. The mixing was required to be completed within 6 hours. Water was added until optimum moisture, or just above, was achieved. The exposed treated soil was sealed by a rubber tired roller, and the soil cured for a minimum of 2 days to a maximum of 7 days, then was placed and compacted to a 2-foot depth in the invert and on the O&M roads, and for an 8-foot horizontal distance on the canal prism side slopes. The material was pulled into the canal invert, where the lime was added and mixed in. The lime-treated material was then compacted back into place. The first rehabilitation, both 2:1 earth and 1-1/2:1 concrete-lined sections, was completed in 1974 and remains in excellent condition. Safety ladders were eventually installed on the earth side slopes because the lime-treated soil remained too firm to make escape possible.

Low Density Foundation Material

Reclamation's Earth Manual [2] states that low density material that has historically never been wet usually has the potential for collapse. These areas should be treated by removal and recompaction or by prewetting. Since both of these solutions are very expensive, a minimal amount of treatment is usually expended, based on the findings of preconstruction geologic exploration and tests performed during construction. For this reason, pockets of low density material may be missed. The problems are usually more pronounced on concrete-lined canals than on earth-lined canals. The problem of collapse becomes apparent in earth canals as soon as the soil collapse begins; therefore, the diagnosis and treatment is easier.

Experiences on Reclamation's concrete-lined Mirdan Canal in Nebraska, constructed in a low density loess, indicate that the most serious problem is likely to occur when the canal prism is constructed in cut on the uphill side of the canal and on fill on the downhill side of the canal. This situation leaves low density material adjacent to the canal lining on the uphill side. If this material becomes saturated, because of cracks in the concrete lining, it collapses, resulting in larger cracks in the lining. A shear plane also forms in the soil during collapse, allowing a path for water to move farther into the low density material. The collapse sequences continue, forming a pattern of cracks and shear planes that look like closed contours, when viewed in plan. As long as the shear planes close on themselves, the water will be contained, but once a shear plane intersects the downhill slope of the canal embankment, water and silt particles can daylight, resulting in a failure and washout of the canal. This scenario occurred on the Mirdan Canal, resulting in a canal washout.

The same series of events started at another location. The canal was temporarily shut down, all cracks and discontinuities in the lining were worked over to eliminate sharp edges, a temporary sheet of PVC was placed over the lining and anchored to the lining at the upstream and downstream ends, and strings of sandbags were placed at intervals along the side slopes to hold the plastic down. This allowed canal operations to continue until the end of the irrigation season.

The following method was used to rehabilitate the Mirdan Canal at both locations. All concrete lining was removed in the damaged area plus some distance upstream and downstream. All suspected low density material was removed and recompacted in place. A 40-mil sheet of HDPE (high density polyethylene), with heat sealed joints, was placed across the entire canal prism, and then Fabric form was placed on the side slopes. When the Fabric form was pumped full of concrete mortar, it matched the original concrete lining. This method was used to provide a watertight lining in case there was still some low density material still present.

After these two areas were repaired, other suspected areas were treated by injecting a silt slurry to consolidate the low density material. Stabilization of low density loess by silt injection, discussed in "The Stabilization of Soil by the Silt Injection Method For Preventing Settlement of Hydraulic Structures and Leakage from Canals" [9], may be used after construction as problems develop in areas that were not identified prior to or during construction.

<u>Silt Foundation Material in Locations with Freeze Potential</u>

Special care should be taken when a canal is constructed on a silt material since an ice crystal formation adequate to damage thin unreinforced concrete lining may develop, even with no free water surface present. A moisture content in silt of 2 percent greater than optimum can lead to damage of unreinforced concrete lining from frost action. If concrete lining is used on frost susceptible silts, all fill material should be placed on the low side of optimum. During construction, the prism should be graded such that storm water will run off and there will be negligible ponding of water. Cracks that do form in the lining should be sealed as soon as possible.

<u>Hydrostatic Backpressure</u>

Hydrostatic pressure in the soil behind any canal lining can be troublesome in many situations. Following are selected situations and solutions:

<u>High Groundwater:</u> If high groundwater is in or develops in the area of the canal, the canal cannot be drained below the groundwater level without damage to the canal. One solution is to keep water in the

canal year-round. If this is not practical, the best solution is to design a new cross section that is wide and shallow, so the canal invert can be raised above the groundwater. If the original canal is concrete lined, the rehabilitation could be buried geomembrane with a sand and gravel cover. The normal depth of this type section is usually less than that for a concrete-lined section, and some minor movement can be tolerated with a buried goemembrane.

Perched Groundwater: Sometimes the canal will act as a dam and will intercept perched groundwater. If damage to the concrete lining is apparent but the damage does not require removal and replacement, then a drainage system can be installed under the O&M road to intercept this grounswater. The drainage can be daylighted into natural drainages that have culverts under the canal. If the lay of the land is such that natural drainages are great distances apart, then the drainage can be taken to pump sumps controlled by floats.

If the damage to the lining is extensive, then an underdrainage system can be placed under the new lining, with the hydrostatic pressure being relieved by flap-valve weeps. These weeps are designed to allow water flow only in one direction. This type drainage system is further discussed in the "Interim Report on Canal Linings Used by the Bureau of Reclamation" [4].

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