RECLAMATION
Managing Water in the West

Design Standards No. 13

Embankment Dams

Chapter 17: Soil-Cement Slope Protection
Final: Phase 4

U.S. Department of the Interior
Bureau of Reclamation

August 2013

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Design Standards Signature Sheet

Design Standards No. 13

Embankment Dams

DS-13(17)-13: Final: Phase 4
August 2013

Chapter 17: Soil-Cement Slope Protection

Foreword

Purpose

The Bureau of Reclamation (Reclamation) design standards present technical requirements and processes to enable design professionals to prepare design documents and reports necessary to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Compliance with these design standards assists in the development and improvement of Reclamation facilities in a way that protects the public's health, safety, and welfare; recognizes needs of all stakeholders; and achieves lasting value and functionality necessary for Reclamation facilities. Responsible designers accomplish this goal through compliance with these design standards and all other applicable technical codes, as well as incorporation of the stakeholders' vision and values, that are then reflected in the constructed facilities.

Application of Design Standards

Reclamation design activities, whether performed by Reclamation or by a non-Reclamation entity, must be performed in accordance with established Reclamation design criteria and standards, and approved national design standards, if applicable. Exceptions to this requirement shall be in accordance with provisions of *Reclamation Manual Policy*, Performing Design and Construction Activities, FAC P03.

In addition to these design standards, designers shall integrate sound engineering judgment, applicable national codes and design standards, site-specific technical considerations, and project-specific considerations to ensure suitable designs are produced that protect the public's investment and safety. Designers shall use the most current edition of national codes and design standards consistent with Reclamation design standards. Reclamation design standards may include exceptions to requirements of national codes and design standards.

Proposed Revisions

Reclamation designers should inform the Technical Service Center (TSC), via Reclamation's Design Standards Website notification procedure, of any recommended updates or changes to Reclamation design standards to meet current and/or improved design practices.

Chapter Signature Sheet
Bureau of Reclamation
Technical Service Center

Design Standards No. 13

Embankment Dams

Chapter 17: Soil-Cement Slope Protection

DS-13(17)-13:[1] **Final: Phase 4**
August 2013

Chapter 17 – Soil-Cement Slope Protection is an existing chapter within Design Standards No. 13 and was revised to include:

- Use of current terminology
- Current state-of-practice
- Photographs and figures for illustration

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[1] DS-13(17)-13 refers to Design Standards No. 13, chapter 17, revision 13.

Prepared by:

Allen H. Kiene, P.E.
Civil Engineer, Geotechnical Engineering Group 2, 86-68312

8/27/2013
Date

Peer Review:

William O. Engemoen, P.E.
Civil Engineer, Geotechnical Services Division, 86-68300

8/26/2013
Date

Security Review:

Robert L. Dewey, P.E.
Technical Specialist, Geotechnical Engineering Group 3, 86-68313

8/27/2013
Date

Recommended for Technical Approval:

Thomas N. McDaniel, P.E.
Geotechnical Engineer, Geotechnical Engineering Group 2, 86-68312

8/28/2013
Date

Submitted:

Karen Knight, P.E.
Chief, Geotechnical Services Division, 86-68300

1/16/2014
Date

Approved:

Tom Luebke, P.E.
Director, Technical Service Center, 86-68000

3/25/14
Date

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Chapter 17

Soil-Cement Slope Protection

17.1 Introduction

17.1.1 Purpose

The purpose of this chapter is to document current guidelines for selecting, designing, and specifying soil-cement slope protection for the upstream face of embankment dams and dikes. Soil-cement slope protection is a mixture of soil, cement, and water compacted to a uniform, dense mass and is used in lieu of riprap. Soil-cement slope protection has proven to be durable, safe, and an economical alternative to the use of riprap on several Bureau of Reclamation (Reclamation) projects. Soil-cement slope protection was first used by Reclamation in a test section for Bonny Reservoir in 1951. Soil-cement slope protection has been considered and/or constructed on a number of embankment dams designed by Reclamation as shown in table 17.1.1-1.

17.1.2 Scope

This chapter pertains primarily to stairstep and plating methods of soil-cement construction as described in Section 17.5.3, “Type of Placement,” for the purpose of protecting the upstream face of embankments from erosion due to wind induced waves and from damage caused by ice and floating debris. The guidance included herein is based on experience from previous Reclamation projects and research. It should be used as the basis for the selection, design, and specification of soil-cement slope protection on Reclamation projects.

Soil-cement has been used to protect upstream areas, in addition to the dam face, from erosion due to wind-induced waves and surface runoff. These areas include reservoir rim slopes and channel linings where thin soil-cement slope protection is constructed parallel to the slope using the plating method of construction. Some guidance is included for the plating method of construction that was used at Merritt, Palmetto Bend, Choke Canyon, and Virginia Smith Dams, as well as at Warren H. Brock Reservoir.

17.1.3 Deviations from Standard

Design of soil-cement slope protection within Reclamation should adhere to the concepts and methodologies presented in this design standard. If deviations from the standard are required for any reason, the rationale for not using the standard should be presented in the technical documentation for the soil-cement slope protection design. The technical documentation should follow the peer review requirements included in the Technical Service Center *Operating Guidelines* [1].

17.1.4 Revisions of Standard

This chapter will be revised as its use and the state-of-practice indicates. Comments and/or suggested revisions should be forwarded to the Bureau of Reclamation, Chief, Geotechnical Services Division (86-68300), Denver, Colorado 80225.

17.1.5 Applicability

This chapter is applicable to the design of soil-cement slope protection for use on embankment structures, including both new and existing dams.

17.2 General Design Considerations

17.2.1 General

The two primary considerations in the design of any feature of a dam are safety and economy. These are the criteria by which all alternative upstream slope protection should be designed.

17.2.2 Economic and Safety Considerations

Historically, riprap has been the most widely used material for upstream slope protection. Many years of acceptable performance and a comparison of construction costs at many damsites have demonstrated that riprap is a safe alternative; usually, it is the most economical alternative. However, there are situations where suitable quality rock is not available within economical haul distances; in these cases, soil-cement may be a viable alternative.

The use of soil-cement for slope protection was first assessed by Reclamation in 1951 by constructing a test section in Bonny Reservoir located in eastern Colorado [2, 3]. Reclamation constructed a stair stepped slope facing along a portion of Bonny Reservoir to evaluate the durability of soil-cement when exposed to severe climatic conditions and the effects of wave action. Figure 17.2.2-1 shows a portion of the Bonny Reservoir test section. The soil-cement was placed using the stairstep method of placement in 6-inch lifts to a horizontal width of 8 feet.

Table 17.1.1-1. Soil-Cement Statistics for Reclamation Projects

Feature	Date constructed	Recommended or specified cement content (% by dry weight of soil)	Unless otherwise noted, cement content (%) required to satisfy Bonny Dam Criteria (note 1)				Cement content (%) used during construction	Soil % fines	Upstream slope (H:V)	Distance to rock	Distance to borrow	Remarks
			Wet-dry	Freeze-thaw	7-day strength	28-day strength						
Bonny test section (near Burlington, Colorado)												
Type A (finer)	1951	10.4	9	10.4	<8	8	10.4	22 to 35	2:1	250 miles		
Type B (coarser)	1951	8.1	<8	8.1	8.1	8.1	8.1	12 to 22	2:1	250 miles		
Merritt Dam (near Valentine, Nebraska) Original construction	1964	14	Test data not reliable				14	18 avg.	4:1	> 100 miles		Much raveling; construction control tests indicate very high strengths were achieved - 7-day 1400 psi, 28-day 1800 psi
Right embankment reconstruction	1968	14	Test data not reliable						10:1	> 100 miles		"Tenting" of upper lift on reconstructed embankment
Cheney Dam (near Wichita, Kansas)	1964	12	8.5	<8	12	11.5	12.5 avg.		2.5:1, 3:1			Average lift thickness 9 inches (range of 5 to 11 inches); only facing failure to date; did not specify Bonny criteria plus 2% cement content
Lubbock Regulating Reservoir (near Lubbock, Texas)	1966	12 for slope; 7 for bottom	9.5	7.6	8.5	8						
Glen Elder Dam (near Glen Elder, Kansas)	1967-68	12	9	<8	10.2	9.6		10 to 25	2.5:1, 4:1			Test section used 8-inch lifts with pneumatic roller only
Downs Dike (near Glen Elder, Kansas)	1967	12	<8	<8	9.2	10		10 to 25	2.5:1			
Cawker City Dike (near Glen Elder, Kansas)	1968	12	<8	<8	9.2	10		10 to 25	2.5:1			
Starvation Dam (near Duchesne, Utah)	1969	12	<10	<10	13	13			2.5:1			Final soil-cement report (date 5/7/1970) not found
Little Panoche Creek Detention Dam (Los Banos, California)	(note 2)	6.3	<6	<6.3	6.3 avg.	6.3 avg.			2.25:1, 2.5:1			Not constructed
Red Bluff Reservoir (near Red Bluff, California)	(note 2)	9	<5.5	<6	7	7.6			2:1, 3:1			Not constructed
Conconully Dam (near Okanogan, Washington)	(note 2)	13	<9	<9	13.5	13.4			2.5:1			Not constructed
Cutter Dam (near Farmington, New Mexico)	1972	8				avg. record core = 920 psi	Range 8 to 9.7; avg. 8.6	24 avg.	2.5:1			
Palmetto Bend Dam (near Edna, Texas)	1979-80	12	<6	<6	10	10			3:1			
McPhee Dam (near Dolores, Colorado)	(note 2)	12	<8	<8	8.7	8.8			dam 2.5:1 dike 3:1	50 miles		Use of fly ash proposed; soil aggregate consisted of crushed Dakota sandstone
Choke Canyon Dam (near Three Rivers, Texas)	1980-82	12	<8	<9.5	<8	9	12 to 10.5		3:1			
Virginia Smith Dam (near Burwell, Nebraska)	1983-85	11	<8	<8	<8	<8	11	7 to 20	3:1	170 miles	3 miles	
Ute Dam Raising (near Logan, New Mexico)	1984	9	Similar to original construction, which specified 7% cement content				Range 8.6 to 13.2; avg. 9.1	11 avg.	2.3:1		1/4 mile	
Monument Creek Dam (Colorado)	(note 2)	12	Same as proposed for McPhee Dam							75 miles	on site	Not constructed
Jackson Lake Dam (near Jackson, Wyoming)	1988	5 to 9	<8	<8	<8	<8	9	7 avg.	3:1	>100 miles	1 mile	Termed "coarse soil-cement" and is essentially a roller compacted concrete with fines but no fly ash
Davis Creek Dam (near North Loup, Nebraska)	1990	10	<8	<8	<8	<8	10	7 to 20	3.5:1, 1:1	170 miles	20 miles	
Warren H. Brock Reservoir (near El Centro, California)	2010	14	≤12	Not tested	12	12	15.8	15 to 40	3:1		on site	
Deer Flat Dam (near Nampa, Idaho)	1990	<10	<10	<10	<10	<10	8.6 avg.	1 to 6	3:1			Soil used in soil-cement obtained from commercial source

Notes:

1. Bonny Reservoir criteria: maximum 6% loss in wet-dry durability test; maximum 8% loss in freeze-thaw durability test; minimum 7-day strength of 600 pounds per square inch; minimum 28-day strength of 875 pounds per square inch.
2. Soil-cement considered in feasibility or specifications design, but not constructed.

Figure 17.2.2-1. Soil-cement test section at Bonny Reservoir, Colorado.

The performance of the Bonny Reservoir test section was observed for 10 years. During that time, the test section experienced an average of over 100 freeze/thaw cycles a year and wind-induced waves that reportedly exceeded 8 feet in height. Due to the lack of a locally available riprap source and the favorable performance of the Bonny Reservoir test section, soil-cement was selected for upstream slope protection at Merritt Dam (completed in 1963). Since about 1960, soil-cement slope protection has been constructed on several Reclamation dams and many other non-Reclamation (public and private) dams that were designed and constructed by others.

One case where a soil-cement slope protection was damaged during severe weather occurred at Cheney Dam in Kansas [4]. In 1964, during construction of the dam, soil-cement was placed on the 2.5H:1V and 3H:1V upstream slopes using the stairstep placing method. The stair steps were 8 feet wide. A 3-day windstorm occurred in March 1971, with a sustained wind velocity of 57 miles per hour and gusts as high as 82 miles per hour. Seven- to nine-foot waves were reported. The damage was repaired in the fall of 1971. Due to additional deterioration of the soil-cement through the years at Cheney Dam, other repairs occurred in 1981 and 2000. Figure 17.2.2-2 shows some of the damaged soil-cement slope protection that was observed in October 1999. Most of the damage occurred along the elevation of the normal reservoir water surface. Previous repairs can be seen immediately behind the person in figure 17.2.2-2.

Figure 17.2.2-2. Damaged soil-cement slope protection on the upstream slope at Cheney Dam, Kansas.

As shown in figures 17.2.2-3 and 17.2.2-4, repairs consisted of placing concrete over the deteriorated soil-cement slope protection. Figure 17.2.2-3 shows the concrete patch above the normal reservoir water surface on the upstream slope of Cheney Dam, looking toward the left abutment. Figure 17.2.2-4 is a closeup view of the concrete patch on the upstream slope, looking toward the right abutment. These photographs were taken during the 2007 Comprehensive Facility Review (CFR) examination.

Figure 17.2.2-3. Upstream slope showing soil-cement slope protection and concrete repairs at Cheney Dam, Kansas.

Figure 17.2.2-4. Closeup view of concrete patch on soil-cement slope protection at Cheney Dam, Kansas.

Due to ice loading and wave action, deterioration of the upstream soil-cement slope protection at Merritt Dam in Nebraska has required ongoing maintenance by the irrigation district [5]. The soil-cement slope protection has been repaired (or patched) several times over the years. Deterioration is most severe in the area of the winter reservoir water surface elevations. Figures 17.2.2-5 and 17.2.2-6 show the condition of the soil-cement slope protection observed during the 2008 CFR examination. Figure 17.2.2-5 shows a portion of the concrete repairs. The stairstep method of placement was used on the 4H:1V upstream slope to place 6-inch-thick (compacted thickness) lifts. The horizontal width of the compacted soil-cement layer was 8 to 10 feet. As long as the soil-cement slope protection continues to be maintained and repaired when necessary, it should continue to perform its intended function.

In spite of some damage and required repairs, the total of initial construction and operation and maintenance costs for the soil-cement slope protection placed at Cheney and Merritt Dams is believed to be significantly less than the corresponding costs associated with riprap slope protection placed on similar dams.

Transverse cracks will occur in soil-cement slope protection and may extend from the top of the slope to the bottom of the slope. Unless these cracks are especially wide, deteriorate with time, or connect together, they are not detrimental to the slope protection. Cracks often fill in with smaller size or wind-blown materials. A beneficial aspect of the cracks is the water pressure relief that they provide. However, additional attention should be paid to the crack surface to ensure that wave action does not draw out the underlying materials over time.

Figure 17.2.2-5. Typical condition of upstream slope protection at Merritt Dam, Nebraska.

Figure 17.2.2-6. Portion of concrete repairs to soil-cement slope protection at Merritt Dam, Nebraska.

17.2.3 Summary

A number of factors must be considered in the development and implementation of an economical and safe slope protection design. Selection of soil-cement for upstream slope protection at a given damsite depends primarily on the availability of suitable quality rock for riprap versus availability of suitable soil for soil-cement. Assuming that suitable material is available for soil-cement slope protection, proper design of soil-cement consists of two major tasks: (1) a comprehensive field investigation and laboratory testing program to determine the required cement content and available soil gradation, and (2) a determination of the dimensions and configuration of the slope protection. New soil-cement slope protection designs are based on the design and performance of the Bonny Reservoir test section, and the refinements are derived from subsequent soil-cement slope protection designs. Proper specification and construction of soil-cement slope protection is derived from previous experience. The most recent specification and construction experience should be reviewed so that the latest knowledge can be incorporated into subsequent specifications.

17.3 Selection of Soil-Cement Alternative

17.3.1 General

Design of Small Dams [6] cites instances where rock riprap was transported over 100 miles for use as upstream slope protection on embankment dams. In these instances, the riprap slope protection was constructed prior to the construction of Bonny Dam in 1951. To obtain suitable rock for riprap slope protection at Bonny Dam, the haul distance was in excess of 250 miles. Based on our present experience with soil-cement slope protection, it is apparent that use of soil-cement for some of these embankments would have been more economical.

17.3.2 Considerations and Guidelines for Planning

In general, soil-cement slope protection becomes cost competitive with placed rock riprap as the distance to the rock source increases. The *Earth Manual* [7] recommends that if the haul distance to a suitable rock source exceeds about 20 miles, and if suitable soil is available at the site, soil-cement should be considered an alternative method of slope protection.

Soil-cement technology was originally investigated as a possible economical alternative to riprap on Reclamation projects in the Great Plains States [2, 3]. However, even in mountainous regions, suitable riprap sources may be at great distances, and soil-cement may be more economical. This was the case at Starvation Dam [8, 9, 10] in Utah where soil-cement was used for slope protection. Also, soil-cement was considered for use at McPhee Dam [11, 12] and the feasibility level designs for the proposed Monument Creek Dam [13], both located in southwest Colorado. The silty-sand aggregate considered for use in the soil-cement at McPhee and Monument Creek Dams was to be obtained from crushed Dakota sandstone. Laboratory tests confirmed that soil-cement of adequate durability and strength could be achieved at typical cement contents. Also, if riprap bedding was expensive or would require two zones of material to satisfy gradation compatibility between the riprap and the embankment materials, soil-cement may be a more economical alternative. Experience with other Reclamation projects indicate that significant cost savings can be achieved with the use of soil-cement slope protection that incorporates suitably graded, silty-sand materials, and suitably graded materials containing significant quantities of gravel sizes.

Cement requirements vary depending on desired properties and type of soils. American Concrete Institute literature states that the cement content may range from as low as 2 percent to as high as 16 percent by dry weight of soil [14]. Typical cement content on Reclamation soil-cement jobs to date has been approximately 12 percent cement by dry weight of soil. At Virginia Smith Dam (formerly Calamus Dam) in Nebraska [15], cement costs were significantly reduced with the use of a blend of coarse and fine sands from different borrow areas. Laboratory tests showed that to satisfy strength and durability minimum requirements, 8-percent cement content was required. This was increased to 11 percent to allow for uncertainties such as severe weather, extremely long fetch, variations in borrow material gradation, and compaction procedures. The pit run (i.e., not blended) dune sand investigated for Virginia Smith Dam would have required about 14-percent cement content after the percentage increase for uncertainties. Thus, a reduction of 3 percent in cement content was achieved using the blended soil.

For the extended facing at the Ute Dam Modification in New Mexico [16, 17], fines were blended into pit run, poorly graded sands, which resulted in a better graded material. The required cement content based on laboratory testing was determined to be about 7 percent (although 9 percent was specified), well below the typical average of 12 percent. The original Ute Dam [18] slope protection incorporated poorly graded sands containing 25-percent gravel sizes (maximum of 3 inches) and required a relatively low cement content of 7 percent. The original slope protection did not experience severe wave action, but it appeared competent even though it had less cement content than Reclamation criteria would have normally required. These examples demonstrate that blending of soils can justify reduced cement contents.

If it appears that riprap sources may not be locally available, and suitable sources of soil for soil-cement may be available, additional material investigations and laboratory testing of the soil to be used in producing soil-cement would be required. Cost comparisons should be made to determine if riprap or soil-cement is clearly the most economical alternative for slope protection. In cases where costs are similar, it may be appropriate to include both alternatives in the final design specifications in the form of alternate schedule items and let the contractor select his preferred alternative.

Significant factors other than cost that must also be considered to ensure that a safe and economical soil-cement slope protection can be designed and constructed include:

- Post-construction embankment/foundation settlement may cause detrimental cracking and distortion of the facing.
- Soil-cement slope protection may not be compatible with dispersive clay embankments unless special design features are included, which may increase costs. The rigid facing might hinder observation of sinkhole development on the upstream face.
- Length of construction season may affect costs. Wet or cold weather would adversely affect soil-cement placement but might not affect riprap placement.
- Soil-cement costs may be increased or decreased for larger or smaller expected wave action. At sites where severe wave action is expected, increased attention to bonding treatment, as discussed in Section 17.5.7, “Additional Bonding Between Lifts,” is recommended. At sites where lesser wave action is expected, reduced facing thickness and cement content may be justified.
- Embankments incorporating soil-cement slope protection may require additional height (increased freeboard) due to higher wave runup on the smoother surface, as discussed in Section 17.5.1, “Freeboard Requirements.”
- Embankment zoning and slopes may be adjusted to take advantage of the impermeable and structural nature of the soil-cement. At Cutter Dam in New Mexico and Merritt Dam in Nebraska, the impervious zone was located adjacent to the soil-cement slope protection to take advantage of the assumed impermeable nature of the soil-cement. At Davis Creek Dam in Nebraska, the strength of the soil-cement allowed the upper 18 feet of the upstream slope to be oversteepened, which significantly reduced embankment volumes and cost.

17.4 Design of Soil-Cement Mix

17.4.1 General

Soil-cement is a well compacted mixture of soil, Portland cement, and water. Sometimes the soil-cement mixture includes the addition of pozzolans. The relative proportions of soil and cement in the soil-cement mixture are based on the results of laboratory tests on specially prepared specimens to determine their durability and strength properties over a range of soil gradations and cement contents. The recommended soil gradation and cement content are determined following comparison of test results with results of similar tests performed for the Bonny Reservoir test section and subsequent projects.

17.4.2 Soil

17.4.2.1 Soil Gradation

A soil-cement mixture of adequate durability and strength can be designed, and slope protection constructed, using almost any type of soil. In general, a wide range of soil types and gradations have been successfully used for highway construction. However, only certain types of soils are preferred for use in soil-cement slope protection on embankment dams. The most desirable soil for soil-cement is silty sand (SM), which has a good distribution of sizes with 15 to 25 percent passing the No. 200 sieve. Other soils may be used; however, more cement may be required to satisfy strength and durability requirements.

17.4.2.2 Reclamation Experience

Soils specified for previous Reclamation embankment dams were typically fine, silty sands that would be classified as SM or SP-SM by the Unified Soil Classification System. Typical soils used for many of the earlier Reclamation soil-cement slope protection projects have had the following characteristics:

Maximum size: 1-1/2 inch
Minimum of 85 percent passing No. 4 sieve
10 to 30 percent passing No. 200 sieve
Low plasticity or nonplastic fines
Clay balls greater than 1-inch size to be removed, with a 10-percent limit on minus 1-inch clay balls

However, it is important to note that several Reclamation projects have used coarser materials. On these projects, specific gradation limits were defined in the specifications. Laboratory tests (p. 7 of reference [4]) have shown that silty sand with a wide range of particle sizes produces soil-cement of acceptable durability and strength at lower cement contents than more uniformly graded fine, silty sands. The cost savings of reduced cement content must equal or exceed the additional costs of special processing in order to be economical. Experience indicates that additional processing costs can be less than the savings in cement costs.

Specifying the soil gradation limits helps ensure that the specified cement content will result in soil-cement of uniform durability and strength. The consistency of the soil gradation that would be achieved by contractor blending procedures and gradation variation of the borrow source should be evaluated. To ensure that soil-cement of required durability and strength is achieved, a conservative cement content based on an assumed worst gradation might have to be specified.

The use of plastic soils (clays) for making soil-cement has not been investigated extensively for slope protection applications for dams. However, significant difficulties in achieving a uniform mixture of soil, cement, and water would be expected. Presence of clay balls is detrimental to achieving a uniform soil-cement mixture. **Therefore, the use of plastic soils should be avoided.**

17.4.2.2.1 Virginia Smith Dam

The soil-cement mix design for Virginia Smith Dam demonstrates how blending operations can result in reduced cement costs. In this case, coarser sands from borrow area D were blended with finer silty sands from borrow areas A and B to produce a more suitably graded silty sand. The contractor was required to perform the necessary blending operations to achieve the specified gradation range. By blending soils, the designer was able to reduce the cement content by 3 percentage points to 11 percent by dry weight of soil. The cement cost savings were estimated at approximately $4 per cubic yard of soil-cement placed, or approximately $700,000 (1985 costs) for the entire job. The additional cost of blending could not be determined but was estimated to be much less than the savings due to reduced cement costs.

In general, before blending is specified, the increased costs of processing and monitoring should be compared to the increased cost of additional cement required for the natural material. Experience at Virginia Smith Dam indicated that a substantial amount of effort is required to combine materials from different sources. Additional equipment (e.g., dozers, front-end loaders, storage hoppers) is required, depending on the contractor's method of blending. Also, when materials from different sources are stockpiled separately, each stockpile must be monitored individually for consistency in gradation and moisture. Uniformity of soil gradation and moisture when introduced into a continuous feed pugmill mixing plant is the most important factor in ensuring uniformity of compacted soil-cement.

There is some debate as to whether blending of different soils was actually accomplished by the procedures used on past jobs. At times, the blended material at Virginia Smith Dam visually appeared gap graded, although this was not indicated by gradation tests. This apparent gap grading could have been due to inadequate blending and could have been the cause of occasional handling and compacting difficulties. Several times, silty materials were added to bring the fines content into specification limits. It appeared that relatively little of the silt was being effectively dispersed throughout the soil as fines because it came through the processing as small to very small silt balls. The designer is advised to consider these economical and technical factors when specifying blending.

17.4.2.2.2 Little Panoche Creek Detention Dam and Red Bluff Reservoir

Soils other than silty sands have been considered by Reclamation for soil-cement slope protection. Relatively coarse soils were investigated for Little Panoche Creek Detention Dam [19] and Red Bluff Reservoir [20]. Laboratory-tested soils for these projects contained up to 50-percent gravel sizes. As a result of laboratory durability and strength testing, recommended cement contents of 6.3 and 9 percent were established, respectively, which is less than the typical 12-percent average cement content. Alternate bid schedules for riprap and soil-cement were included in the specifications. Despite the potential cost savings of the low cement contents, the riprap alternative was selected for these projects. Some difficulty was expected in mixing and placing soil-cement of such coarse gradation in a uniform layer and probably contributed to selection of the riprap alternative over the soil-cement alternative. It should be noted that the original Ute Dam facing used aggregate containing 25-percent gravel sizes with no significant placement difficulties. The mixing and construction methods used in the placement of roller-compacted concrete may allow the use of soil-cement that contains coarser aggregate. The designer should consider using coarser aggregate (when available) in soil-cement slope protection.

17.4.2.2.3 Jackson Lake Dam

An example of the use of coarse soil-cement was at Jackson Lake Dam, Wyoming. Jackson Lake Dam was originally constructed by Reclamation in 1911. Modifications were completed to the dam in the late 1980s to correct seismic dam safety deficiencies. The modifications included placement of soil-cement slope protection on the upstream face of the dam. Figure 17.4.2.2.3-1 shows the condition of the soil-cement slope protection observed during the 2010 CFR examination.

Soil used for the soil-cement at Jackson Lake Dam consisted of 100 percent passing the 1-1/2-inch screen, an average of 50 percent passing the No. 4 sieve, and an average of 7 percent passing the No. 200 sieve. This soil was similar to the type of aggregate used in roller-compacted concrete. Soil-cement at this project was placed using a paving machine and compacted by a steel drum roller. No significant mixing, placing, or compaction problems were noted, although particular attention was given to ensuring proper moisture content and minimizing segregation. This particular mix, when placed wet of optimum, resulted in an almost "flowing" mix, which made traveling on it and compacting it difficult. Since the material was relatively coarse, all phases of the operation were monitored to ensure that a well-graded blend of materials was being placed during construction.

Figure 17.4.2.2.3-1. Soil-cement slope protection at Jackson Lake Dam, Wyoming.

17.4.2.2.4 Conconully Dam

Relatively fine soils were investigated for use in the soil-cement for the Conconully Dam Modifications [21]. The tested soil was a rock flour with 95-percent fines and 5-percent sand. A recommended cement content of 13 percent was established based on laboratory durability and strength tests. Laboratory testing indicated that the fine gradation would be difficult to mix to obtain uniform cement distribution. Since a suitable riprap source was located and used to construct the upstream slope protection, the suitability of this material for use in making soil-cement has not been verified by field performance.

17.4.2.3 Borrow Sources

Soil is usually obtained from a borrow area that is explored in detail to ensure that sufficient quantities of acceptable soils are available. A relatively uniform or homogeneous deposit is most desirable. Stratified deposits may be used, provided that selective excavation and processing is practical and economical compared to using other potential sources. Selective excavation and mixing during stockpiling may be necessary to provide a soil that is uniform and homogeneous in grading and moisture content to the extent practicable. Screening equipment may be necessary to remove oversize particles, and to remove or reduce the size of sand, silt, and clay aggregation, referred to as “clay balls,” which tend to form in borrow areas containing lenses of clay.

The following factors should also be considered when evaluating borrow sources for soil:

1. An excellent soil gradation is a silty sand with a wide range of particle sizes. More distant borrow sources containing this material naturally (i.e., special processing not required) may be more economical than nearby sources containing soil of a less desirable gradation. The break-even haul distance is difficult to determine.

It might be economical to blend materials of inferior gradations from nearby sources to achieve the preferred gradation. This scheme, described earlier for Virginia Smith Dam, was also specified for Davis Creek Dam.

2. Proposed borrow sources should be evaluated to determine the potential for clay and silt ball formation. These inclusions are rounded balls of predominantly clayey fines that do not break down during normal processing. Their presence in the compacted lifts is evident by a dotted or bumpy appearance. This indicates that zones of lesser durability, slab strength, and interlayer bonding may exist and may affect the performance of the facing as a unit. Observations during construction also indicate that clay balls tend to be tracked over the lift by equipment. Bonding is reduced unless the lift is thoroughly broomed before the next lift is placed. Reference [4] recommends that, "During the investigation stage, the material should be screened at its natural moisture to obtain an estimate of the amount of clay balls present in the deposit." The presence of more than 10-percent clay balls in an auger-hole sample, even smaller clay balls, is an indication of likely problems during construction. Clay balls may not be as apparent in test pits or other sampling methods.

3. Proposed borrow sources should be evaluated to determine the acidity of the soil. A pH of less than 5.5 can negatively affect the cement reaction.

17.4.3 Type of Cement

Any type of Portland cement meeting the requirements of the latest American Society for Testing and Materials (ASTM), American Association of State Highway and Transportation Officials, or Federal specifications may be used. Type I, or normal Portland cement, is most commonly used because the special properties of other types of Portland cement are not usually required for soil-cement slope protection. However, selection of the type of cement to be used depends on the potential for sulfate attack and/or the potential for the occurrence of alkali-aggregate reaction. The guidelines that are used for concrete structures are also applicable to soil-cement slope protection [22].

There are numerous examples of the effect of sulfate attack on concrete structures; however, examples of its effect on soil-cement slope protection were not found in the literature. Nevertheless, where detrimental levels of soluble sulfates exist, soil-cement slope protection would be expected to experience the same expansion and disruption that might occur in a concrete structure.

As discussed in the *Concrete Manual* (pp. 10, 11, 43-48 of reference [22]), detrimental levels of soluble sulfates may be present in the ground water, mix water, soil aggregate, and adjacent soil. Sulfate attack potential increases with increasing concentrations of soluble sulfates in the soil and mix water. To mitigate the reaction, sulfate-resistant cements should be specified in accordance with *Concrete Manual* guidelines (p. 11 of reference [22]). Type II cement is recommended for soil-cement slope protection that is exposed to moderate sulfate attack; type V cement is appropriately specified where more severe sulfate attack is expected. If soluble sulfates are present in very small quantities below the threshold level for concern, consideration should be given to specifying type II cement, which is normally available at the same cost as type I cement.

It is also possible for soil-cement slope protection to crack and deteriorate as a result of alkali-aggregate reaction. This reaction occurs between alkalis in the cement and the mineral constituents of certain aggregates. The observed effects in affected concrete have included random cracking, excessive expansion, and generally accelerated deterioration. The reaction can be mitigated by the use of low-alkali cements, use of nonreactive aggregate, or by the addition of certain amounts of selected pozzolans. This reaction has not been observed in any soil-cement slope protection constructed to date, possibly because of the low cement content and small volume of voids in the finished product as compared to conventional concrete structures.

The potential for sulfate attack and alkali-aggregate reaction should be considered in field and laboratory investigations and in the final design. Samples of local ground water and proposed soil sources should be tested to determine appropriate cement type.

Pozzolans have been used as a partial replacement for cement on some soil-cement projects. Pozzolans could include Class F or Class C fly ash or slag cement [14].

17.4.4 Water Quality

Water from most sources, whether raw or treated, is suitable for use with soil and cement. However, water should not contain substances which could cause excessive deterioration. Recent specifications have required that the quality of water used to produce soil-cement be the same as that required for concrete structures. Specifically, the water should be free from objectionable quantities of organic matter, alkali, salts, and other impurities that might inhibit its reaction with the cement. Of particular concern are soluble sulfate salts. Cement specifications permit a maximum 3,000-milligrams-per-liter concentration of soluble sulfates and, as discussed previously, would require a special type of cement. To verify a concern, the durability and strength of laboratory specimens prepared with high-quality water would need to be compared to specimens prepared with the poorer-quality water.

It should be noted that sea water has been successfully used as mixing water at several projects including the cooling water reservoir at the Barney M. Davis

Power Station in Texas. The *Concrete Manual* [22] indicated instances of acceptable concrete made with sea water, as well as other situations where addition of sodium chloride solutions in the mix water resulted in significant strength losses.

In general, specifications for soil-cement slope protection should require water of a quality that would be acceptable for use in concrete structures. The *Concrete Manual* (pp. 68-70 of reference [22]) contains additional information on the effects of objectionable materials in the mix water.

17.4.5 Laboratory Testing Program

A laboratory testing program should be conducted to establish the required soil gradation and cement content for the soil-cement slope protection. The scope of the program discussed herein does not include any testing that may be necessary to assess special requirements, particularly regarding sulfate attack or alkali-aggregate reaction potential. The test specimens should, **as much as possible**, represent the anticipated in-place properties of the soil-cement slope protection. Also, recommendations on soil gradation and cement content should take into account anticipated deviations between laboratory-controlled behavior and the expected range of field behavior.

The laboratory testing program consists of standardized durability and strength tests. Throughout its life, the soil-cement slope protection will be subjected to various erosive forces including repeated cycles of:

- Wetting and drying in the form of reservoir fluctuation and wave splashing
- Freezing and thawing due to seasonal temperature changes
- Abrasion due to reservoir ice and wind, and wave-tossed debris
- Uplift due to dynamic wave forces on poorly bonded soil-cement lifts, which can act as unsupported cantilevered slabs

Standardized wet-dry and freeze-thaw tests are conducted to assess the durability of a range of soil-cement mixtures. These tests evaluate cylinder durability by measuring the accumulated weight loss of the cylinder after 12 cycles of wet-dry or freeze-thaw, followed by calibrated brushing. Unconfined compressive strength tests are also conducted on prepared cylinders. The correlations developed in the laboratory for durability and strength tests are then compared to compressive strength tests performed during construction control to assess if soil-cement of adequate durability is being achieved.

The standardized durability and strength tests are performed on specially prepared specimens. Specimen preparation involves uniformly mixing, placing, compacting, and curing cylinders of the soil-cement. All specimens are compacted near or at optimum moisture content to maximum laboratory dry density (or to a percent of maximum laboratory dry density selected by the designer).

Durability and strength tests are made on prepared cylinders of soil-cement for a range of soil gradations and cement contents. A typical testing program might consist of performing standard wet-dry (ASTM D 559), freeze-thaw (ASTM D 560), and compressive strength (ASTM D 1633) tests on one set of cylinders prepared at the estimated cement content and two other sets prepared at 2 percentage points above and below the estimated cement content. This set of tests is repeated for each specific soil gradation within the range of soil gradations.

The soil-cement design for a specific project should consider whether or not freeze/thaw testing is desired in preliminary laboratory studies. If the project is located in an area not subjected to freezing temperatures, the freeze/thaw durability testing may not be required. However, freeze/thaw testing may still be performed to evaluate the performance (general durability) of the soil-cement mix.

The soil gradation is also a variable to be investigated. Representative samples of the finest, average, and coarsest material should be submitted for laboratory testing. For projects prior to Virginia Smith Dam, generally only suitable soils from the nearest sources were tested because haul distance was believed to be the governing criterion. However, extensive testing now indicates the potential for significant cost savings in the form of lower required cement contents when suitably graded silty sands are used. The soil gradation is as important as the haul distance in arriving at the total cost. The scope of the testing and exploration program proposed for a particular project should consider this factor.

Depending on the project, it may be necessary to test the full range of possible gradations. The ranges of gradations to be tested depend on experience gained from similar sites, as well as on whether unprocessed soils from specific borrow sources or specially processed soils derived from multiple sources are to be used. Sampling and testing costs could be minimized by comparing current project characteristics to past similar projects. For example, the extensive laboratory testing program performed for Virginia Smith Dam was useful in reducing the required amount of testing for nearby Davis Creek Dam.

Details on specific procedures for sample preparation and testing are available from Reclamation's Materials Engineering and Research Laboratory Group and are contained in the *Earth Manual* [23]. In developing sampling and testing programs, a typical series of durability and strength tests with test cylinders prepared at three different cement contents and at the natural material gradation requires as much as 2,000 pounds of soil (forty 50-pound sacks) for jobs where different soil blends are tested.

17.4.6 Selection of Cement Content and Soil Gradation

17.4.6.1 Soil Gradation

It is again emphasized that silty sand with a wide range of particle sizes typically results in soil-cement of acceptable durability and strength at a lower cement content than uniformly graded sands provide. Also, with the advent of better mixing, construction techniques, and testing methods associated with roller-compacted concrete technology, coarser materials with significant gravel contents have been shown to provide good results. The lower cement content is probably the best indicator of cost savings. Haul distance and processing effort to achieve a specified gradation also affect costs, but often to a lesser degree. The gradation that is ultimately selected will also necessarily depend on the availability of materials. These factors and the results of laboratory durability and strength tests for the range of gradations and cement contents investigated should be considered in establishing the soil gradation to be incorporated into the specifications.

17.4.6.2 Cement Content

The cement content to be specified is a matter of judgment based on results of laboratory durability and strength tests; experience gained from design, construction, and performance on previous jobs; and other factors which relate to the amount of acceptable risk for the specific site.

The following is taken from reference [24]:

> "For the earliest soil-cement facings, the selection of the cement content after the laboratory tests was based on criteria established for highway construction. Two percent of cement by weight was then arbitrarily added to allow for the durability required by additional exposure and erosion which would occur on water retaining embankments."
>
> "More recently, the selection of cement content has been influenced by the successful performance of the soil-cement test section at Bonny Dam. Laboratory test results on the soil proposed for slope protection on a new dam are compared with the results of tests of soils used at Bonny Reservoir Test Section. Cement contents providing results equal to or exceeding those for soils used at Bonny Reservoir are considered adequate for the new dam."

The minimum durability and strength criteria using Reclamation procedures (often referred to as the “Bonny criteria”) for specimens compacted to the laboratory maximum dry density are:

- Wet-dry durability - maximum specimen weight loss of 6 percent after 12 cycles
- Freeze-thaw durability - maximum specimen weight loss of 8 percent after 12 cycles
- Minimum specimen 7-day unconfined compressive strength of 600 pounds per square inch (lb/in^2) (based on specimens having length to diameter ratio of 2:1)
- Minimum specimen 28-day unconfined compressive strength of 875 lb/in^2 (based on specimens having length to diameter ratio of 2:1)

Note that the compressive strength requirements for specimens cast using ASTM D 559 (4.0- by 4.584-inch specimens) are a minimum of 675 lb/in^2 at 7 days, and 1,000 lb/in^2 at 28 days. This adjustment results from different cylinder sizes (and, thus, different length-diameter ratios) in Reclamation versus ASTM test procedures. The compressive strength specimens for soil-cement testing at Warren H. Brock Reservoir were cast using ASTM D 559 and were tested in accordance with ASTM D 1633, which resulted in higher specified strength criteria.

Since construction of the Bonny Reservoir test section, soil-cement slope protection has been constructed at several Reclamation water-retaining structures, as shown on table 17.1.1-1. A review of the laboratory test reports, design documentation, and construction reports disclosed that the specified cement content was generally 2 percentage points greater than was necessary to satisfy the Bonny criteria. The purpose of the increase was reportedly to allow for construction variances such as soil gradation variability; nonuniform mixing of soil, cement, and water; and zones of inadequate compaction. In these cases, a 2-percentage-point field variation in cement content was assumed to be possible.

Increasing the specified cement content above the minimum criteria is warranted for other reasons. For some structures, the soil-cement slope protection may be considered an important component of the impermeable zone. Other slope protection may be considered critical to protecting an underlying erodible zone (e.g., Virginia Smith Dam). In these cases, it has been considered critical to maintain the integrity of the slope protection, and increasing cement content was considered the best way to achieve this.

The Bonny Reservoir test section has performed adequately for over 60 years under relatively severe climatic and loading conditions. It is estimated that the test section has withstood several cycles of significant wave action and many cycles of wet-dry and freeze-thaw. However, sites exist that would be expected to experience more severe loading conditions. At these sites, where the adequate performance of the Bonny Reservoir test section is only partly relevant, increasing cement content is probably justified. Such situations might include slope protection that is subjected to wind-generated waves greater than that predicted for the Bonny Reservoir test section (approximate 1-mile fetch in the northwest direction), such as at Virginia Smith Dam, or slope protection subjected to harsher climates such as Jackson Lake and Deer Flat Dams. Conversely, sites exist that would experience less severe loading conditions. Such situations might include slope protection that is subjected to less severe wave action, possibly due to smaller fetch distances (e.g., Cutter Dam), or that is subjected to milder climates.

Several additional comments follow which designers should consider in the selection of the final cement content:

1. The routine procedure of specifying a cement content 2 percentage points greater than the minimum required by the Bonny criteria may be overly conservative in many cases. Although design documentation is not specific, on most previous projects where the decision was made to require a cement content increase, that decision was based on anticipated differences between laboratory testing and field conditions. These differences include natural soil gradation variability and possible inconsistent construction quality. While these are valid concerns, the designer should consider that construction quality is probably more consistent on post-Bonny projects. The use of central mixing plants (known as "pugmills"), rather than the tractor-drawn, in-place mixer used on each lift at the Bonny Reservoir test section, as well as improved construction control, have improved the average quality of recently constructed soil-cement slope protection. Since the Bonny Reservoir test section is performing adequately for the construction quality achieved at this site, it may be overly conservative to routinely increase cement content for reasons of possible construction variability.

   Soil gradation variability significantly affects durability and strength. For this reason, laboratory tests should be performed on the expected range of gradations and the cement content should be specified accordingly. Gradation limits should also be specified and construction control testing should be employed to ensure that these limits are met. It may not be feasible to control gradation. This situation may occur because borrow area characteristics are not as predicted or because the contractor's excavating, blending, and mixing operations are inadequate.

   Because of these uncertainties, an initially higher cement content is probably warranted until potential construction problems are resolved. Reclamation, when responsible for quality assurance, has routinely allowed a cement reduction when field strengths are high. A useful technique was employed at Choke Canyon Dam, Texas [25, 26], which allowed for an adjustment downward from the maximum specified cement content as the contractor's operation became more consistent. The specifications required a cement content of 12 percent, which was decreased at 0.5-percentage-point increments because construction control inspection and testing indicated that the minimum 7-day strengths could be consistently achieved at the lower cement content. At Choke Canyon Dam, the cement content fluctuated between 12 and 10.5 percent, depending on the contractor's ability to achieve a consistent product.

2. A review of laboratory test results from previous Reclamation soil-cement projects indicated that Bonny strength criteria usually controlled the minimum required cement content (see table 17.1.1-1). That is, for the minimum cement content, the wet-dry and freeze-thaw weight losses were well below the maximum weight losses permitted by Bonny criteria. Increasing cement content above the minimum is not required to ensure durability.

   The adequacy of the Bonny strength criteria is difficult to assess. The strength of the soil-cement is important to the resistance of the slabs to breaking off from wave action. Most soil-cement slope protection projects constructed to date have performed satisfactorily. The only notable exception was the moderate and severe damage to Cheney Dam in 1966, 1969, and 1971. It is interesting to note that the minimum cement content was specified for this soil-cement (i.e., the routine 2-percentage-point cement content increase was not used). It should also be noted that Cheney Dam has a much longer fetch in the prevailing wind direction than the Bonny Reservoir test section (8 miles compared to 1 mile, respectively). The experience with Cheney Dam indicates that slab resistance to breakage must be improved for soil-cement slope protection that is subjected to wave loads similar to those experienced at Cheney Dam. The Bonny strength criteria may be sufficient for soil-cement slope protection that experiences wave load magnitudes similar to the Bonny Reservoir test section but may be inappropriate for greater effective fetches and wave loads.

3. There is some debate as to whether increasing cement content or improving layer bonding would best improve resistance to slab breakage from wave action. Improving bond, if effective, is significantly less expensive than increasing the cement content of the entire soil-cement slope protection. Increasing cement content only in selected zones of expected severe wave action may be economically competitive. A combination of the two schemes may be best. An extensive laboratory test program [27] indicated that bonding between layers could be significantly improved by dry cement or cement slurry applied between layers. Test sections were conducted at Cutter [28, 29], Palmetto Bend [30, 31], and Jackson Lake Dams to evaluate the effectiveness of alternative layer

bonding schemes. Brooming only, brooming plus dusting with dry cement, and brooming plus applying a cement paste or slurry were investigated. The slope protection was cored to examine and test the degree of bond between layers. Only the Palmetto Bend Dam results were located in available literature. Coring during this study indicated 25- to 50-percent intact bonds in the cement-treated sections and no bond in broomed only sections. The results from Jackson Lake Dam also indicated approximately 50-percent intact bonds after coring in treated areas. Due to the disruptive action of the coring process, quantitative improvements are difficult to assess. However, it can definitely be concluded that cement treatment significantly improves layer bonding. **Use of a bonding agent between soil-cement lifts is recommended.**

In the previous version of this design standard, a simple beam analysis was performed to assess whether increasing the cement content significantly improved the breaking resistance of unsupported cantilever slabs. For a typical 3H:1V slope, increasing cement content 2 percentage points increased breakage resistance an estimated 17 percent. This amount of increased resistance would not be particularly effective in preventing damage due to wave action.

It was noted in several laboratory reports that the standard Reclamation criterion for specifying cement content was the minimum cement content required to satisfy the Bonny criterion plus 2 percent. This statement is not strictly correct, even though it has been the method used to specify cement content for most slope protection constructed to date. The designer is encouraged to carefully consider the factors discussed above, the results of recent research, and the ongoing performance of existing soil-cement slope protection before specifying the cement content.

17.5 Design Details

17.5.1 Freeboard Requirements

The procedure for calculating freeboard requirements for dams with soil-cement slope protection is essentially the same as that used for dams with riprap slope protection. The only major difference is in the calculation of wave runup. Wave runup on stairstepped soil-cement surfaces is often estimated to be 50 percent greater than wave runup on riprap. The soil-cement stairsteps eventually weather to a rough, feathered edge. The stairsteps are less effective in dissipating waves than riprap but are more effective than smooth concrete slopes. Therefore, the wave runup for stairstep soil-cement is intermediate between riprap and smooth concrete. Due to the relatively smooth slope, the wave runup for plating soil-cement slope protection is greater than that experienced using riprap or stairstep soil-cement. Procedures for computing wave runup and freeboard requirements are given in *Design Standard No. 13, Embankment Dams*, Chapter 6, "Freeboard."

The greater wave runup for soil-cement slope protection may, in most cases, require a greater embankment height than would be required if riprap were used. This factor should be considered when developing cost estimates for comparing soil-cement and riprap alternatives (see Section 17.3.2, "Considerations and Guidelines for Planning").

17.5.2 Extent of Protection

17.5.2.1 Areas to be Protected

In general, most areas of the embankment, abutments, and reservoir rim, which would otherwise require substantial erosion protection, could be adequately protected by soil-cement slope protection. In addition to the upstream face slope protection, soil-cement could also be used for the following areas:

- On the dam crest to provide a subgrade for, or serve as, the crest surfacing and to protect against potential extreme wave runup and washover during severe windstorms
- Along intake channels of appurtenant structures and diversion channels to prevent erosion from wave action and diversion flows
- On upstream impervious blankets to protect against wave and surface runoff erosion (particularly longshore transport of materials due to wind)
- Along critical zones on the reservoir rim subjected to wave and precipitation erosion

17.5.2.2 Degree of Protection

The degree of protection required for a particular area depends on the severity of expected loading conditions, the reliability of the construction, and the criticality of the area to the safe performance of the structure. Critical areas where most severe loadings are expected and which entail difficult construction would require the highest degree of protection.

Increasing the degree of protection can consist of one or a combination of the following:

1. Increasing the vertical and/or lateral extent over which the slope protection is constructed.

2. In areas where extent is already specified:

- Increasing the cement content of the mix
- Providing a bonding treatment between lifts
- Providing more frequent monitoring and control of construction, especially controlling soil gradation

17.5.2.3 Upstream Face

In general, the embankment upstream face requires a high degree of protection due to the severe loadings caused by wind and wave action and the critical need for protecting erodible embankment materials that underlie the slope protection. The slope protection normally extends from the crest of the embankment down to below the inactive water surface. In a lateral direction, the slope protection should extend to the same limits as that specified for riprap placement and may be continuous with areas on the abutments or reservoir rim requiring protection. The U.S. Army Corps of Engineers practice of providing bands of riprap only at critical reservoir levels may be a consideration for soil-cement slope protection.

The guidelines and factors discussed in Section 17.4.6, "Selection of Cement Content and Soil Gradation," for specifying cement content apply to critical areas under severe loads such as upstream face slope protection.

17.5.2.4 Dam Crest

A lesser degree of protection is warranted for the dam crest horizontal surface. If soil-cement is required for the crest surface for reasons of potential extreme wave runup, a lesser cement content is warranted because the loadings would occur infrequently and would be of short duration. A lesser cement content is warranted for soil-cement used as subbase material. However, it may not be practical to adjust the cement content if the volume to be placed is small.

Experience at Virginia Smith Dam showed that the shrinkage cracks that occur in soil-cement were reflected through the asphalt surface course. These cracks are unsightly and require periodic maintenance (filling). The designer should be aware of the potential for cracking in this type of application.

17.5.2.5 Channels

Standard guidelines are not available for waterways, such as canals, and diversion and intake channels. The required strength is estimated to be less than that required for the upstream slope protection on a dam due to less severe wave action. Durability requirements are the same. Because of this, a relatively thin 9- to 12-inch veneer of soil-cement placed and compacted parallel to the slope is usually specified. Typical density requirements are specified; however, the method of compaction is not specified. Experience with channel construction at Palmetto Bend [30, 31], Choke Canyon [25, 26], and Virginia Smith Dams indicates that adequate compaction on the slope can be achieved by pneumatic or smooth-drum vibratory rollers and, to a somewhat lesser extent, by crawler tractors. Section 17.6.3, “Transporting, Spreading, and Compacting,” discusses in more detail compaction on channel side slopes.

To date, the specified cement content in these areas has been the same as that used for upstream slope protection. A lower cement content may be warranted, considering the less severe service loads expected, providing that thorough compaction and required densities can be obtained.

17.5.2.6 Upstream Impervious Blankets

Soil-cement blankets constructed to be upstream seepage barriers are expected to experience much less severe loadings than upstream slope protection. Some minor wave action and longshore transport erosion could occur. Upstream impervious blankets usually have flat slopes so that stairstep construction is not used (analogous to floors of channels). Instead, lifts are placed parallel to the slope. Despite the different construction method, a lesser degree of protection is generally warranted. Cement contents may be reduced, and bonding treatments may not be required. Thicker lifts (12 inches) compacted by smooth-drum vibratory rollers were successfully used for the protective covering on the Virginia Smith Dam upstream impervious blanket, resulting in cost savings over earlier use of two 6-inch lifts. One guideline found in the literature concerned the Lubbock Regulating Reservoir. At that site, the upstream slope protection was specified to have 12-percent cement content, while 7 percent was specified for the upstream impervious blanket.

17.5.2.7 Reservoir Rim

The degree of required protection varies with each situation. However, all of the considerations pertaining to the upstream face slope protection should also be considered in the design of the reservoir rim slope protection.

17.5.3 Type of Placement

The stairstep method and the plating method are used for constructing soil-cement slope protection. The stairstep method of placement is used for slopes that are exposed to moderate-to-severe wave action. The stairstep method consists of constructing nearly horizontal lifts of compacted soil-cement. Each successive lift is set back by an amount equal to the compacted lift thickness times the cotangent of the slope angle. This results in a stairstep pattern approximately parallel to the final embankment slope angle, as illustrated in figure 17.5.3-1. This method is used on the upstream faces of dams and may be required on the abutments and reservoir rims, depending on the degree of slope protection deemed necessary. Figure 17.5.3-2 shows the completed stairstep soil-cement placement at Warren H. Brock Reservoir in California. Due to the potential for high velocity flows that may cause erosion of the soil-cement, the stairstep method of soil-cement placement was used in the area adjacent to the inlet-outlet structures.

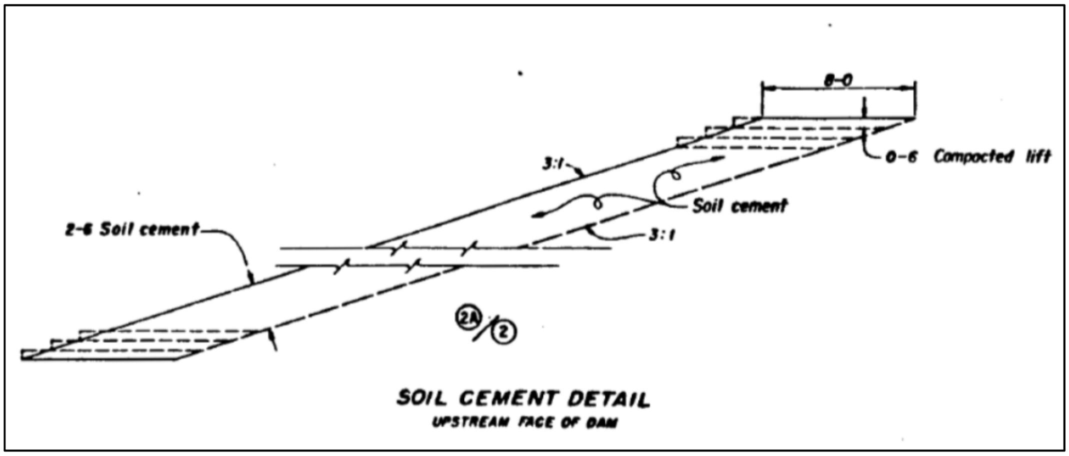

Figure 17.5.3-1. Typical stairstep soil-cement configuration.

Figure 17.5.3-2. Stairstep soil-cement at Warren H. Brock Reservoir, California.

The plating method of placement is defined as slope protection consisting of one or more lifts of soil-cement placed parallel to the slope. The plating method of placement can be considered for use on small dams where wave action is not severe. Even for small dams, this method is generally not considered for use in areas expecting significant wave action, such as the upstream face of the dam and reservoir rim. The plating method uses less soil-cement than the stairstep method;

however, the flatter slopes required for placement provide little resistance to wave runup and more freeboard may be necessary. Figure 17.5.3-3 shows the completed plating soil-cement placement at Warren H. Brock Reservoir in California.

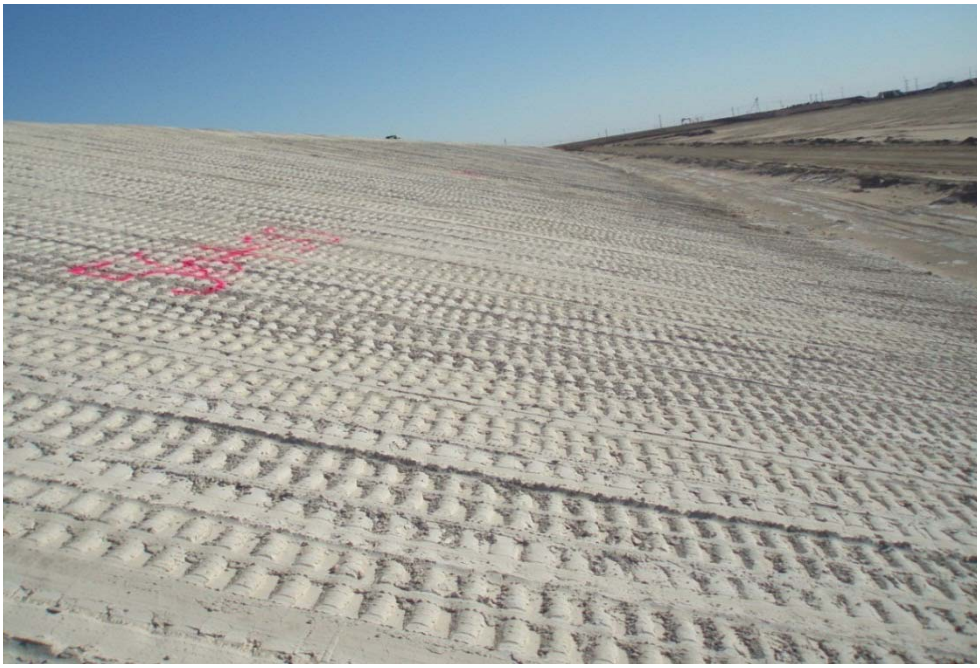

Figure 17.5.3-3 Plating soil-cement at Warren H. Brock Reservoir, California.

Lifts placed parallel to the slope result in construction joints that are either parallel to, or perpendicular to, the flow of water. The steepness of channel side slopes requires that lifts be placed down the side slope, which results in vertical construction joints that are perpendicular to waterflow. Blankets and beaching slopes are generally flat enough to allow lifts to be placed either up, down, or along the side slope.

Lifts placed up or down the slope result in vertical construction joints that are perpendicular to the dam axis (in line with the wave runup direction) and are easier to construct. Figures 17.5.5-2 and 17.6.5-1 (shown later in this chapter) show examples of vertical construction joints that result from the placement of plating soil-cement up the embankment slope. Rather than operating compaction equipment across the slope, compaction equipment is operated up and down the slope, thereby providing safer construction practices.

Except when placed on flat slopes and upstream blankets, equipment-compacted plating lifts that are placed parallel to and across the slope (horizontally), rather than up or down the slope, are less desirable. As the slope becomes steeper, constructability and safety become concerns. The horizontal joint between the soil-cement lifts becomes a plane of weakness, and it is difficult to ensure uniform compaction of the soil-cement.

In general, the steepest practical slope for utilizing the plating method for soil-cement construction is considered to be 3H:1V. Construction using either stairstep or plating methods is difficult or impossible in restricted areas around structures and around curves without special construction methods. Fillets of lean concrete and special compaction methods (smaller rollers, wheel rolling, hand compaction) have been successfully used in these areas.

17.5.4 Slope Protection Thickness

The thinnest possible soil-cement slope protection should be specified to minimize cost. Construction limitations generally control soil-cement thickness. For stairstep construction, an approximate 8- to 10-foot horizontal width is required to accommodate placing and compaction equipment (see discussion in Section 17.6.3, "Transporting, Spreading, and Compacting." This results in an approximate 2- to 3-foot normal thickness of soil-cement for most embankment upstream slopes. For example, for a horizontal width of 8 feet, a slope of 3H:1V, and 6-inch thick lifts, the resulting minimum thickness of soil-cement slope protection is approximately 2.5 feet. Figure 17.5.4-1 shows soil-cement slope protection normal thicknesses resulting from an 8-foot horizontal width placed on different slopes.

Facing Normal Thickness vs Slope

		8.0 ft. horizontal width					
		1H to 1V	1.5H to 1V	2H to 1V	2.5H to 1V	3H to 1V	4H to 1V
6-Inch lift thickness	outer	6.4	5.0	4.0	3.3	2.8	2.2
	inner	5.7	4.4	3.6	3.0	2.5	1.9
12-Inch lift thickness	outer	6.0	4.7	3.8	3.2	2.7	2.1
	inner	5.7	4.4	3.6	3.0	2.5	1.9

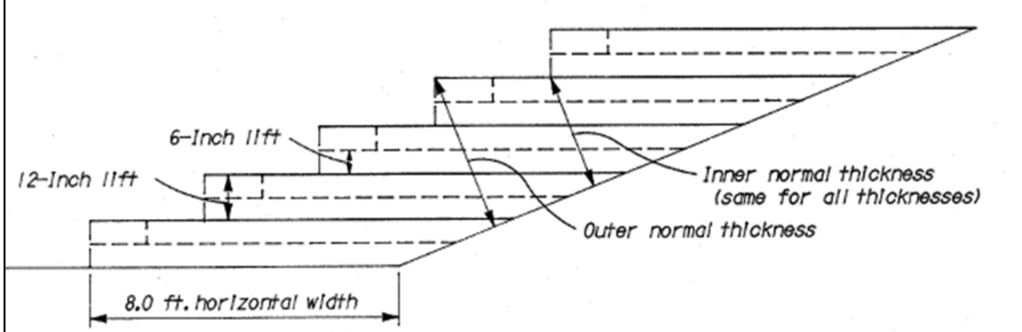

Figure 17.5.4-1. Soil-cement normal thickness at various slopes.

In general, Reclamation has specified a minimum 8-foot horizontal width for upstream soil-cement slope protection constructed using the stairstep method of placement independent of whether a particular site would require a 1-foot- or a 3-foot-thick riprap slope protection. However, it is possible to construct thinner stairstep slope protection with standard-width equipment and smaller spreaders. The soil-cement and a narrow lift of embankment fill are placed side by side, and the roller covers both materials. This method of construction requires that both materials can be compacted with the same roller and that the placement and compaction procedures prevent contamination of the soil-cement. This method was used to construct the soil-cement slope protection for the original Ute Dam [18].

Thinner soil-cement slope protection using the stairstep method of placement has also been constructed with a conveyor placement system instead of dump trucks. Narrower dump trucks are not available; hence, a minimum horizontal width is required to accommodate them. However, narrower spreaders and rollers are available and can be used with conveyors to construct thinner slope protection. The designer should ensure that any narrow roller specified has sufficient weight to provide adequate compaction.

If narrower stairstep construction is employed, consideration should be given to the actual mechanics of how the soil-cement slope protection resists wave action. Part of the resistance is due to the mass of the soil-cement slope protection, and part of it is due to the strength of the soil-cement slope protection as a unit.

17.5.5 Lift Thickness

Lift thickness of soil-cement, using the stairstep method of placement, ranges from 6 to 9 inches. Figure 17.5.5-1 shows the partially constructed, 9-inch-thick, soil-cement lifts placed using the stairstep method of placement at Warren H. Brock Reservoir in California. The photograph is taken at the transition of the soil-cement placed using the stairstep method and that placed using the plating method.

There are some advantages to using thicker lifts in stairstep construction. Advantages include:

- Fewer bonding surfaces are created, which would reduce the total cost of any special required bonding treatments.

- Should the cantilever slab of an individual lift break off, the larger block formed by the thicker lift would not easily move away from the slope by wave action.

Figure 17.5.5-1. Stairstep soil-cement placement at Warren H. Brock Reservoir, California.

Disadvantages include:

- The amount of waste (size of feathered edge) is increased. In this case, the feathered edge is the outer edge of the soil-cement lift that receives minimal compaction.

- Potential difficulties in achieving adequate compaction throughout the entire lift thickness.

With some experimentation with compaction and placement procedures, adequate compaction of 12-inch, soil-cement lifts can be achieved. At Virginia Smith Dam, adequate compaction using a smooth-drum vibratory roller was achieved for 12-inch-thick compacted lifts on the upstream blanket.

There has been some debate on whether the longer cantilever slabs, resulting from thicker lifts, are more resistant to the type of breakage observed at Cheney Dam. As mentioned earlier, the previous version of this design standard included a simple beam analysis of the unsupported cantilever slab formed by stairstep construction. The analysis indicated that slab resistance to breakage by uplift forces is independent of lift thickness. The analysis indicated that slab resistance increases with increasing unconfined compressive strength (i.e., increasing cement content) and with steeper slope protection.

Lifts placed parallel to the slope (plating) have been constructed in single and multiple lifts at past Reclamation construction projects. Lift thickness has ranged from 6 to 12 inches. Soil-cement slope protection will typically require plating thicknesses of 9 to 12 inches minimum. A single 9-inch lift of soil-cement (as shown on figure 17.5.5-2) was placed on the geomembrane on the 3H:1V embankment slopes at Warren H. Brock Reservoir in California.

Figure 17.5.5-2. Plating soil-cement placement at Warren H. Brock Reservoir, California. (Note the vertical construction joint.)

The soil-cement slope protection placed on the 3H:1V side slopes of the spillway inlet channel at Palmetto Bend Dam consisted of a single 12-inch lift, while the floor consisted of a 3-foot-thick layer constructed in 6-inch compacted lifts. At Virginia Smith Dam, the soil-cement slope protection placed on the 3H:1V river outlet works intake channel side slopes and floor consisted of a single 12-inch lift. The soil-cement slope protection that was placed on the 10H:1V beaching slope at Merritt Dam was placed in two 6-inch lifts. Movement and buckling occurred in the upper 6-inch lift of the beaching slope at Merritt Dam. Figure 17.5.5-3 shows a picture of this damage It is not known if this "tenting" effect would have occurred if the soil-cement slope protection had been placed as a single lift. **Given this performance issue and the potential for poor bonding between lifts, single lifts are preferred to multiple lifts when the plating method is specified.** If multiple lifts are specified, placement of bonding treatment between lifts is recommended (see Section 17.5.7, “Initial Bonding Between Lifts”).

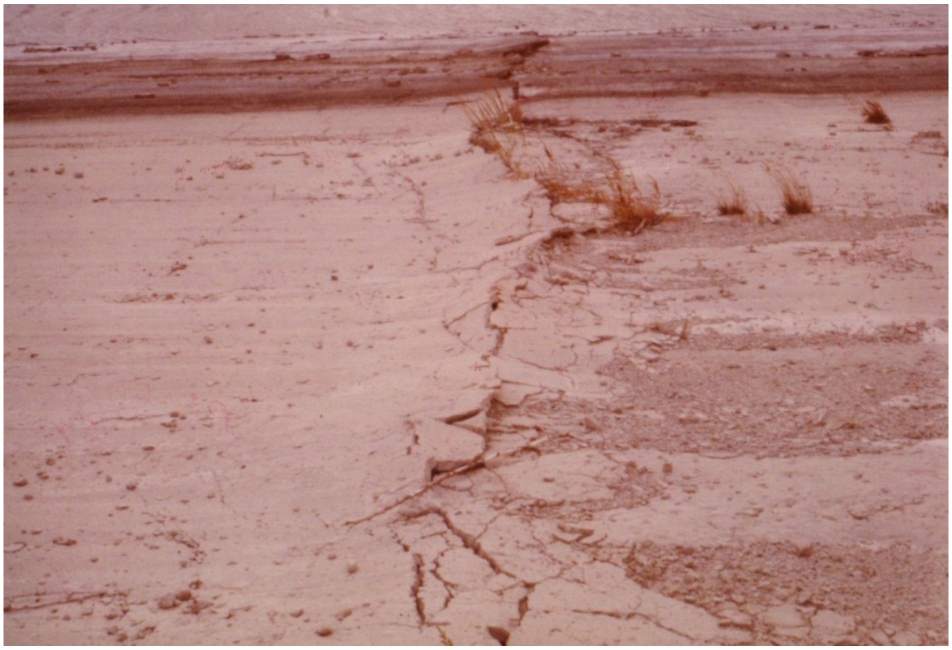

Figure 17.5.5-3. Damaged soil-cement slope protection on the 10H:1V beaching slope at Merritt Dam, Nebraska.

17.5.6 Toe, Structure, and Abutment Details

17.5.6.1 General

A number of design details are discussed below that may be required or useful at some sites. The need for these details depends on the extent and degree of protection considered appropriate for a particular site.

17.5.6.2 Toe Berm

Toe berms have been constructed for some Reclamation jobs. The purpose of the berms is to provide an initial level working surface, which aids in construction and provides a limiting lowest elevation below which upstream slope protection is not required. The usual configuration of the toe berm has included a 15- to 20-foot-wide berm at an elevation 3 to 5 feet below a selected low water surface elevation, typically the top of inactive or dead water surface. The soil-cement slope protection was embedded 1.5 to 3 feet below the berm to prevent undermining of the slope protection from wave action at the lowest reservoir elevation and from precipitation runoff along the upstream groins. The slope protection/berm contact V-notch was backfilled with riprap on the earliest jobs but is backfilled with zoned embankment materials on recent jobs.

Palmetto Bend and Choke Canyon Dams did not include the toe berm. The soil-cement slope protection at Palmetto Bend Dam was terminated at a break in slope slightly below the inactive water surface. The soil-cement slope protection at Choke Canyon Dam extended to original ground surface without construction of a berm. A suitable working surface and adequate erosion protection are obtained when the starting elevation of embedded soil-cement lifts is specified.

At Davis Creek Dam, the soil-cement extended to original ground surface, without a berm. However, an 8H:1V sloping fillet of compacted clay with a maximum thickness of 5 feet was placed over the soil-cement/original ground contact to provide erosion and undercutting protection.

17.5.6.3 Structure Details

The interface between the upstream face slope protection and intake areas of appurtenant structures usually has abrupt changes in shape, tight curves, and restricted working spaces. Compaction is difficult or impossible to achieve in many instances and is generally an expensive operation for the contractor. Lean concrete was substituted for soil-cement in these areas at Palmetto Bend Dam. The lean concrete mix contained a typical 1-1/2-inch maximum size aggregate gradation and 3-1/4 sacks of cement per cubic yard. This mix was easier to place than specially compacted soil-cement and resulted in higher strengths.

Specially compacted soil-cement may be used in tight areas; however, if compaction is difficult, consideration should be given to increasing the cement content of the mix used in these areas. Figure 17.5.6.3-1 shows special compaction adjacent to the concrete structure at Warren H. Brock Reservoir in California.

Figure 17.5.6.3-1. Special compaction of soil-cement adjacent to concrete structure at Warren H. Brock Reservoir, California.

17.5.6.4 Abutment Details

Depending on the site topography, the embankment/abutment contact may be abrupt or smooth, and it may be subjected to significant to negligible erosion forces due to waves and surface runoff. Also, the soil-cement may contact a rock or soil abutment. These factors should be considered in design of the abutment detail.

For abrupt contacts, such as changes in slope or steep abutments (an example of a steep abutment is Cutter Dam), it may be difficult to obtain adequate compaction of the soil-cement. These narrow areas also tend to concentrate erosional forces. Specially compacted soil-cement or a lean concrete fillet may be specified. If the soil-cement slope protection contacts a soil abutment, special measures such as a riprap groin and/or embedding the slope protection may be advisable to prevent erosion of underlying earthfill and subsequent undermining of the slope protection.

For smooth contacts in soil, either embedding the soil-cement slope protection or utilizing a compacted clay fillet may be sufficient to control erosion at the groin. Smooth contacts in rock may not require special treatment.

17.5.7 Additional Bonding Between Lifts

The soil-cement slope protection at Cheney Dam experienced damage that resulted from a severe windstorm. At Merritt Dam, the soil-cement slope protection was damaged during average wave action. The damage generally consisted of broken and displaced slabs at both dams and included erosion of underlying embankment earthfill at Cheney Dam. The damage was believed to be the result of inadequate strength of the individual unsupported cantilever slabs formed as a result of stairstep construction. Since blocks of soil-cement remained intact, failure of the slope protection did not appear to result from inadequate durability of the soil-cement. Failure of the slope protection likely occurred along lift lines due to uplift caused by wave action.

As previously discussed in Section 17.4.6, “Selection of Cement Content and Soil Gradation,” two alternatives for addressing the potential for damage caused by wave action are considered feasible:

- Increase the cement content to increase the flexural strength of the unsupported cantilever.
- Increase the bond strength between layers.

Providing tensile reinforcement is not considered practicable or economical because of the construction difficulties involved and increased material costs.

As previously discussed, analysis of a uniformly loaded cantilevered beam representing the unsupported slab of an individual stairstep indicated that increasing cement content by 2 percentage points did not significantly increase resistance to dynamic wave forces and is expensive.

Also discussed previously, increasing bond strength seems to have good potential for minimizing slab breakage. Brooming alone does not appear to be effective in increasing bond strength. **Providing a cement slurry or cement paste bonding treatment is recommended between all soil-cement lifts.** Dry cement powder has also been successfully used as a bonding treatment. The dry cement is placed uniformly across the width of the soil-cement lift at an application rate of about 1 pound per square yard. The cement should be applied to the moistened surface immediately prior to placement of the next lift. One problem with using dry cement is that it is easily blown away. For this reason, the cement slurry and cement paste treatments are recommended over the use of dry cement powder. Cement slurry having a water-cement ratio of 0.70 was used at Warren H. Brock Reservoir to provide the bonding agent between soil-cement lifts. The slurry was mixed in a batch plant and transported to the site. Figure 17.5.7-1 shows the placement of the slurry at Warren H. Brock Reservoir.

Figure 17.5.7-1. Spreading of cement slurry bonding agent at Warren H. Brock Reservoir, California.

Elapsed time between final compaction of a lift and placement of the overlying lift is an important factor in achieving bond between lifts. Better interlayer bond was achieved at Ute Dam when the elapsed time between lifts was minimized. At this site, three lifts that extended for half the dam crest length were constructed each day instead of completing a single lift for the entire crest length before the next lift was placed. Two placement operations were used at Cheney Dam, which also resulted in good bond between lifts. Cores obtained for documentation of soil-cement placement indicated a higher occurrence of bonding between lifts that were constructed in this way.

The bonding between lifts is improved by scarifying the soil-cement surface upon which the next lift is to be placed. A power-driven broom can be used to scarify the surface to a depth of 1/8 to 1/4 inch. Figure 17.5.7-2 shows the scarified soil-cement lift at Warren H. Brock Reservoir. Loose material and accumulated debris should be removed immediately prior to placement of the next lift. Figure 17.5.7-3 shows the equipment used to scarify and clean the soil-cement lift at Warren H. Brock Reservoir. Scarification is particularly critical at the end of each day's work, or whenever construction operations are interrupted for more than 1 hour.

Figure 17.5.7-2. Scarified soil-cement lift at Warren H. Brock Reservoir, California.

Figure 17.5.7-3. Cleaning soil-cement lift at Warren H. Brock Reservoir, California.

17.5.8 Drainage Considerations

There is some debate as to whether drainage of the soil-cement slope protection should be provided. During rapid drawdown of the reservoir after a prolonged high reservoir level, the soil-cement slope protection may inhibit dissipation of embankment pore water pressure. The unrelieved pressures may be sufficient to displace the slope protection, possibly resulting in cracking, distortion or slipping of the slope protection. However, none of these conditions have been observed in any Reclamation projects to date.

Most Reclamation soil-cement projects have not included drainage features. However, one example where drainage features were utilized was Merritt Dam. The right embankment soil-cement slope protection at Merritt Dam [4, 31, 32, 33] was provided with three rows of 3- to 5-inch-diameter weep holes at three elevations. The weep holes were drilled into the soil-cement slope protection after construction and included 118 holes on 10-foot centers at elevation 2,944; 82 holes on 10-foot centers at elevation 2,939; and 33 holes on 10-foot centers at elevation 2,933. The weep holes were backfilled with gravel. The upstream face is 10H:1V. The soil-cement slope protection was immediately underlain with embankment zone 2 consisting of sand.

With the exception of soil-cement slope protection placed at Virginia Smith and Starvation Dams, the soil-cement slope protection at Reclamation dams was constructed on the impervious zone (some embankments were zoned, while others were essentially homogeneous). At Virginia Smith and Starvation Dams, the soil-cement slope protection was placed against relatively pervious shell zones. For these sites, adequate drainage was believed to be provided by the transverse shrinkage cracks which develop in the soil-cement lifts on 10- to 25-foot intervals.

Warren H. Brock Reservoir is unique for Reclamation in that the impervious element of the embankment is a geomembrane protected by soil-cement slope protection. Due to concerns with rapid drawdown at Warren H. Brock Reservoir, drainage features were provided between the geomembrane and the plating soil-cement lift. The drainage features consist of geotextile and geonet composite placed on the 3H:1V slope and a gravel drain placed at the toe of the slope.

Currently, it appears that drainage is not required unless there is going to be an unusually severe drawdown condition.

17.6 Specifications and Construction Considerations

17.6.1 General

The specifications paragraphs and drawings should contain all the requirements that the contractor needs to construct the soil-cement slope protection. Construction considerations explain design rationale and anticipated conditions and should be included in the specifications paragraphs so that field personnel and the contractor can understand the intent and intricacies of the design. The reader should refer to current specifications to aid in preparation of these documents.

The specifications requirements and construction considerations are too numerous to repeat here. A summary of significant items is discussed below. The reader is referred to final construction reports of previous jobs and other articles [2, 3, 4, 35, 36, 37], which describe the actual construction procedure in detail.

17.6.2 Proportioning and Mixing

The construction step that has the greatest tendency to vary is the production of the soil-cement mix from the time the raw materials are selected to the moment the mix is discharged from the mixer. To ensure that a consistent mix of the required soil gradation, moisture content, and cement content is produced, the following should be incorporated into the specifications:

- The acceptable range of soil gradations and the borrow sources should be specified. The borrow sources should be thoroughly investigated in conjunction with the laboratory test program to establish the gradation limits.
- The approximate cement content by dry weight of soil should be specified. The actual cement content will be established during construction. Depending on the contractor's operations and the variability of the soil gradation, the actual cement content can vary.
- For most projects, the mixing plant should be specified to be a stationary twin-pugmill with a rated plant capacity of at least 200 cubic yards per hour. Experience has shown that this type and capacity of equipment can produce adequate quantities of the required uniform mixture within required time limits. Figure 17.6.2-1 shows the pugmill used to make soil-cement at Warren H. Brock Reservoir. A smaller capacity plant may be adequate for projects where the volume of soil-cement is less substantial. In those cases, a rotary drum mixer may be allowed; however, longer mixing time and more frequent drum cleanout may be necessary.

Figure 17.6.2-1. Pugmill used to make soil-cement at Warren H. Brock Reservoir, California.

Water content limits at the time of compaction have been previously specified to be between 1 percentage point wet and 1 percentage point dry of optimum. Most Reclamation jobs constructed to date have used a water content at or drier than optimum. When the mix is too wet, trafficability and compaction difficulties can occur, and excessive distortion or cracking of lifts can occur during compaction. If the mix is too dry, specified densities may not be achieved. The climate at the site should be considered when specifying the moisture content. If the site is located in a dry climate, higher moisture contents may need to be specified due to evaporation. The moisture content at Warren H. Brock Reservoir (located along the California-Mexico border) was specified to range from 1 percent dry to 2 percent wet of optimum. The designer should consider specifying a range of placement moisture content of 2 percent dry to 2 percent wet of optimum. Testing should be conducted to ensure that adequate density can be achieved for the specified moisture limits.

17.6.3 Transporting, Spreading, and Compacting

The procedures for constructing the stairstep slope protection are relatively routine and have been consistently followed at Reclamation projects. Procedures for constructing soil-cement slope protection using the plating method are somewhat less routine; however, several projects such as the Cedar Creek Balancing Reservoirs located near Kennedale, Texas; Reuter-Hess Dam located near Parker; Colorado; and Reclamation’s Warren H. Brock located near El Centro, California, have soil-cement slope protection that was placed using the plating method. The following construction details are emphasized regardless of which placement method is used:

- The elapsed time between mixing and compacting must be specified to ensure that soil-cement can be adequately compacted before the soil-cement lift hardens. Haul time from the time of discharge from the mixer to spreading in the fill is limited to 30 minutes. Final compaction for a lift must be completed within 60 minutes after spreading. For unusually dry and hot climates, this period may have to be less than 60 minutes. For example, at Davis Creek Dam, where hot, dry, and windy conditions were anticipated, the specifications required final compaction to take place within 30 minutes after spreading. One additional standard requirement for all jobs is that any material left unworked for more than 30 minutes must be removed and replaced.

- The soil-cement mixture should be transported to the site in trucks having clean, tight, and smooth beds to facilitate construction and minimize contamination of the mix. Trucks may have to be covered to prevent excessive drying by wind or contamination of the mix by rain or dust.

- For stairstep and plating construction, the surface on which the soil-cement lift is to be placed should be specially prepared. The soil surface should be compacted to specified in-place density and moisture requirements. The soil-cement surface should be broomed to clean the surface, kept moist to improve bond between layers, and treated with the recommended bonding procedure. The soil-cement mixture is then spread to the required lines and grades and to a thickness which would result in the required compacted thickness (an approximate 9-inch spread thickness results in a 6-inch compacted lift thickness). Stairstep lifts may be placed horizontally or on a slope (8H:1V) toward the reservoir. Placing on a slight slope increases the working width and better accommodates construction equipment. However, blocks loosened from sloping lifts are more easily moved away from the slope face by wave action (e.g., Merritt and Cheney Dams). Consideration should be given to requiring horizontal lifts placed by narrower equipment, if necessary, as discussed in Section 17.5.4, "Slope Protection Thickness."

For plating construction on relatively level surfaces (channel floors, blankets), construction practices are the same as for stairstep construction.

Plating construction has been accomplished on 3H:1V and flatter slopes. To date, spreading and compacting procedures have generally not been specified by Reclamation. Instead, an end-product density is specified, and the contractor's spreading and compacting operations must produce soil-cement slope protection that has the required density, usually 98 percent of Proctor maximum dry density (95 percent at Palmetto Bend Dam and 97 percent at Warren H. Brock Reservoir), although specific density criteria are not always specified. Use of a pneumatic-tired roller on the side channel slopes was specified at Virginia Smith Dam, although the contractor was allowed to use a crawler tractor instead. Crawler tractors attained a lower (but acceptable) density at Virginia Smith and Palmetto Bend Dams, but the procedure produced rough surfaces containing loose pieces of soil-cement. If crawler tractors are used, consideration should be given to requiring either flat dozer tracks or cleaning of the rough and loose surface materials remaining after compaction. With regard to spreading efficiency with crawler tractors, it was found on the Virginia Smith Dam channel construction that the best product, in terms of a facing of relatively uniform thickness with minimal waste, was achieved when the materials were spread from top to bottom (rather than from bottom to top). However, careful attention must be paid to the operation to ensure reasonably uniform thickness.

The plating method of placing soil-cement slope protection was used at Warren H. Brock Reservoir. The embankment is 28 feet high and has 3H:1V slopes. Soil-cement was spread in lifts using low ground pressure, wide-track, crawler type dozer and compacted using vibratory steel wheeled rollers. Lift thickness, moisture content, and density requirements were specified. Spreading operations and the number of roller passes were not specified. The soil-cement was not placed directly on a soil foundation; instead, it was placed on geotextile and geonet composite, which overlaid 60-mil, high-density polyethylene geomembrane. The geomembrane provided the water barrier for the embankment. Figure 17.6.3-1 shows the soil-cement spreading and compaction operations at Warren H. Brock Reservoir.

Figure 17.6.3-1. Plating soil-cement placement at Warren H. Brock Reservoir, California.

On early Reclamation stairstep soil-cement projects, the lifts were usually compacted by six passes of a sheepsfoot roller, followed by four passes of a pneumatic roller. Figure 17.6.3-2 shows the compaction of 6-inch, soil-cement lifts using sheepsfoot and pneumatic rollers at Starvation Dam in Utah. Vibratory compaction, using vibratory steel drum rollers, has also been used to compact soil-cement. Use of pneumatic-tired rollers or steel drum rollers is now the most common equipment used to compact soil-cement in stairstep applications. Figure 17.6.3-3 shows the use of a vibratory steel drum roller compacting 9-inch, soil-cement lifts at Warren H. Brock Reservoir in California.

Specific moisture content and density requirements for soil-cement construction have been included in most recent specifications. The initial moisture content of the soil-cement at the batch plant ranges from 1 percent dry to 2 percent wet of optimum moisture. Due to variations in the material, and the climate at the site, the initial moisture content should be determined daily. At the start of compaction, the moisture content of the soil-cement mixture should be at optimum moisture or slightly above. Proper moisture is necessary for compaction and for hydration of the cement. It is better to have a slight excess of moisture rather than a deficiency when compaction begins. The moisture content should be adjusted as required to achieve the required density with minimum rutting of the lift surface. Specific density requirements range from 95 to 98 percent of maximum density. The specifications at Warren H. Brock Reservoir required that the soil-cement be compacted to a minimum of 97 percent of maximum density. However, the requirement was later revised to accept at least 95 percent of maximum density. The Davis Creek Dam soil-cement specification required that the soil-cement be uniformly compacted to a minimum density of 97 percent and an average density of 98 percent of the laboratory maximum dry density. On any soil-cement job, construction control testing is required to verify that adequate density is achieved throughout the entire lift.

Figure 17.6.3-2. Placement of soil-cement slope protection, Starvation Dam, Utah.

Figure 17.6.3-3. Vibratory steel drum roller used to compact soil-cement at Warren H. Brock Reservoir, California.

Test sections were constructed at Glen Elder and Virginia Smith Dams and at Warren H. Brock Reservoir. The test sections at Glen Elder and Virginia Smith Dams were used to investigate thicker lifts and compaction procedures, while the test section at Warren H. Brock Reservoir was used to evaluate placement and compaction procedures for the plating soil-cement. Adequate bond and density were obtained for thicker lifts at Glen Elder Dam with 10 passes of a pneumatic roller. Six-inch stairstep and 12-inch plating compacted lifts were adequately compacted by a combination of six vibratory and static passes of a smooth-drum vibratory roller at Virginia Smith Dam. This roller caused surface shearing, which may have resulted in a somewhat weaker bond between lifts. However, with some experimentation on construction procedures and finding a roller with a weight that is compatible with the soil-cement mix, these problems may be overcome. At Warren H. Brock Reservoir, the contractor's original plan was to use a yo-yo setup with a dozer, excavator, pulley, cables and a Cat CS76 roller to compact the soil-cement using the plating method. Due to surface shearing and inadequate strength, the proposed method of compaction did not provide satisfactory results, and the contractor eventually used the Sakai CV550T roller compactor shown in figure 17.6.3-1 to compact the soil-cement. It is important to stress that if the specifications define, or if the contractor proposes a different method of compaction than normally used on Reclamation jobs, a test section should be utilized at the start of soil-cement construction to evaluate roller performance and to develop the details of the compaction procedure. Adequate time should be allowed to evaluate test section results.

If haul roads are placed on the soil-cement, a minimum of 2 feet of cover is required to protect the soil-cement from damage caused by equipment travel. Two feet of cover is also required for ramps placed on the soil-cement slope for the entire length of the haul ramp. The soil-cement slope protection on Virginia Smith and Palmetto Bend Dams was damaged by construction equipment because of inadequate soil cover near the top of the haul ramp.

17.6.4 Curing and Bonding

All permanently exposed soil-cement surfaces are to be cured for a minimum of 7 days. Water curing by sprinklers or a fog spray, or curing by providing a minimum 6-inch-thick moist earth cover, is acceptable. If soil cover is used to cure the soil-cement, the earth cover must remain moist for a period of 7 days. Once curing is complete, the earth cover should be removed. If it is not removed, it can produce an unsightly appearance due to erosion resulting from wave action and rainfall. Figure 17.6.4-1 shows the use of sprinklers for curing of the plating soil-cement at Warren H. Brock Reservoir.

Compacted surfaces of soil-cement that are to receive an overlying or adjacent layer of soil-cement must be kept clean and moist in order for the next layer to have an opportunity to bond. Cleaning the bonding surface is accomplished by using a power-driven steel broom to remove all loose and uncemented material. Unless an overlying soil-cement lift is to be placed within 1 hour, the contractor should not be permitted to broom sooner than 1 hour after compaction because the broom tends to remove excessive amounts of the lift surface that have not hardened sufficiently. This results in unnecessary waste and increases cement cost. In the past, this brooming has also been used to striate the lift surface with the intent of improving the (mechanical) bond between lifts. As mentioned earlier, coring, test sections, and studies have suggested that brooming alone does not appear to contribute significantly to improved bonding.

Figure 17.6.4-1. Sprinklers used for water cure at Warren H. Brock Reservoir, California.

As discussed in Section 17.5.7, "Additional Bonding Between Lifts," special bonding treatments such as dry cement powder or slurry can be used to improve the bond between lifts of soil-cement. In preparing the specifications, the designer should consider the following:

- Dry cement powder treatment can be easily blown off the bonding surface, unless applied to a dampened surface.
- Cement slurry treatment can dry rapidly, as can a cement paste.

- Whichever treatment is selected, it should be applied immediately before the next layer is spread.

17.6.5 Construction Joints

Construction joints may occur in both transverse and longitudinal directions at stoppages of work. However, specific locations of these joints do not need to be specified. The joint should be trimmed to form a straight vertical joint. Figure 17.6.5-1 shows trimming of the construction joint at Warren H. Brock Reservoir. Prior to placement of the next lift, any loose material should be removed to provide a clean surface, the surface should be moistened, and bonding treatment should be applied as discussed in Section 17.6.4, "Curing and Bonding." When constructing stairstep placements, successive lifts should not have their construction joints at the same location because this would create the potential for a continuous vertical joint.

Figure 17.6.5-1. Trimmed vertical construction joint at Warren H. Brock Reservoir, California.

17.6.6 Construction Control

17.6.6.1 General

Construction control procedures are divided into two general categories:

- Controlling the quality of the soil-cement mix
- Controlling the quality of the facing construction

17.6.6.2 Mix Quality

The following general procedures have been developed to ensure that a soil-cement mix of the required gradation and cement content is produced:

- Gradation, specific gravity, Atterberg limits, and moisture content should be run often on the final blended soils which are being fed into the mixing plant. Verification of the soil gradation is of primary importance. The contractor's excavation and blending procedures should also be monitored.

- Experience has shown that calibrating and maintaining a calibration on the soil, cement, and water feeding devices are important to achieving proper proportioning of ingredients. Cement and water feed are more easily controlled than soil feed. Due to varying soil properties, such as gradation and moisture content, more effort is usually required to calibrate the dry weight production of the soil. It is recommended that a “no cement” shutoff control be used to ensure proper cement feed. Also, the specifications should include a requirement that all feed devices be calibrated daily when material properties change and after shutdowns due to repairs or weather.

- At Warren H. Brock Reservoir, the heat of neutralization method (ASTM D 5982-07, entitled “Determining Cement Content of Fresh Soil-Cement”), was used to determine the cement content during construction.

17.6.6.3 Slope Protection Construction Quality

Laboratory and field tests are performed to verify the quality of the mix that is produced and the construction procedures that are used. Construction procedures are monitored to verify that adequate density and bonding are achieved.

Samples of the soil-cement mix are taken from the batch and tested in the laboratory to determine compaction characteristics and cement content. Specimens for testing are prepared at about the same time as compaction on the placement to account for the time-dependent effects on soil-cement.

An in-place density test is performed as soon as possible after compaction near the spot on the facing which contains the same material as the laboratory compaction specimens. Determination of in-place density at Warren H. Brock Reservoir, using the nuclear gage, is shown on figure 17.6.6.3-1, and figure 17.6.6.3-2 shows the sand-cone method. Measured and specified densities are then compared to determine if the lift was adequately compacted.

Unconfined compression specimens are prepared to a standard compactive effort required by the test method, at the moisture content found in the site sampled material. These laboratory specimens are tested at various ages to determine strength properties and to ensure that the soil-cement is adequately gaining strength with age.

Figure 17.6.6.3-1. Use of nuclear gage to determine in-place density at Warren H. Brock Reservoir, California.

Figure 17.6.6.3-2. Use of sand-cone method to determine in-place density at Warren H. Brock Reservoir, California.

17.6.6.4 Record Coring

Core holes are drilled in the facing at selected locations to verify the thickness of the soil-cement facing and to obtain specimens for laboratory durability and strength testing. Unconfined compressive strength and durability test results on these cores are compared with preconstruction test results and design criteria to determine adequacy of the facing. Core holes should be backfilled with concrete or soil-cement.

17.6.7 Measurement and Payment

Two pay items are provided in the bidding schedule for costs associated with furnishing and placing soil-cement slope protection. One item is for the cost of furnishing and handling cement for soil-cement slope protection. In this item, the designer is cautioned to carefully specify exactly what cement will be paid for (i.e., all cement, including waste and overbuild [one extreme], or perhaps only the cement within the specified lines and grade [the other extreme]). The second item is for all other costs associated with constructing the facing. Cement is usually paid for by the ton. The construction cost item is paid for by the volume of compacted soil-cement in place to the specified lines, grades, and dimensions. Experience has shown that a 10- to 20-percent overrun for construction waste is possible. To be fair to all parties concerned, the specifications should be particularly clear on whether overbuild will be paid and, if so, how it will be paid (refer to Davis Creek Dam specifications for an example). The Virginia Smith Dam construction staff recommended that relatively close tolerances be required for soil-cement construction to control the contractor's tendency to overbuild.

17.7 References

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