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Twenty-Year Performance of Soil-Cement Dam Facings

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SYNPOSIS The soil-cement slope protection on three Bureau of Reclamation projects has been damaged enough to require repair. They were the first three Bureau embankments to utilize soil-cement in place of riprap and have been in service about 18 to 20 years. The soil-cement facings on other Bureau dams are in excellent condition. The lack of bond between the soil-cement lifts in combination with severe weather and wave action appear to be the main factors contributing to the damage. Laboratory tests and field test sections indicate that cement applied between the soil-cement lifts may be a practical solution to prevent damage to the facing when severe weather and wave conditions exist. Calamus Dam, currently under construction, will have an extensive test section incorporated into the soil-cement facing where both dry cement and a cement slurry will be used between soil-cement lifts.

INTRODUCTION

Since 1963, the USBR (Bureau of Reclamation) has used compacted soil-cement as an upstream slope protection for 10 embankments. Another dam utilizing soil-cement is under construction and two more are planned in the near future. The first two dams to use soil-cement slope protection have been in service for about 20 years. Merritt Dam, built in 1963, is currently undergoing repair of its soil-cement facing. Cheney Dam, built in 1964, has had the soil-cement facing repaired three times. Lubbock Regulating Reservoir was built in 1966 and the soil-cement facing is presently in need of repair. Another four of the embankments have been in service for about 15 years and the soil-cement is in excellent shape. The damage that has occurred is apparently due to two factors, the lack of bonding between the soil-cement lifts and the severity of the weather and the wave action on the facing. All of the facings have poor bond between the lifts; however, the weather conditions at Merritt and Cheney are more severe than at the other locations.

HISTORY OF SOIL-CEMENT SLOPE PROTECTION ON USBR PROJECTS

Soil-cement slope protection was first tried (1951) by the USBR on an experimental test section at Bonny Dam in eastern Colorado. A special embankment with a soil-cement facing was constructed at a site expected to get maximum destructive exposure. The test section was separate from the dam, and the soil-cement was constructed using mixed-in-place techniques. The facing was inspected frequently, and after 10 years of evaluation, soil-cement was added to USBR specifications as an alternate to riprap as a method of upstream slope protection, as discussed by Holtz and Walker (1962).

Merritt Dam was the first (1963) dam to have soil-cement slope protection, followed closely by Cheney Dam (1964). In the period 1966 to 1969, five other embankments were constructed with soil-cement facings. Two of these were dikes with minimum wave action on them. The embankment at Lubbock Regulating Reservoir completely encloses the reservoir and soil-cement was used on the interior slopes and on the bottom. The remaining two, Glen Elder Dam and Starvation Dam, are major earth dams.

A small dam with a very sheltered reservoir was faced with soil-cement in 1972. The rubble left from construction has not even been washed away at the water surface.

A dam constructed in Texas in the late 1970's used soil-cement as slope protection for an embankment for a railroad relocation through a portion of the reservoir as well as for the upstream slope protection of the dam. Another dam in Texas that utilized soil-cement slope protection was constructed in 1980-81 and has not yet had water against the facing. Calamus Dam in Nebraska is currently under construction, and soil-cement will be used as slope protection and also as a cover for a portion of the upstream blanket. Two additional dams to be built in the near future will probably use soil-cement slope protection.

All of the soil-cement facings to date were constructed using a central batch plant and compacted with sheepsfoot rollers and pneumatic rubber-tired rollers. The lifts were compacted to 6 inches for all of the features except three which utilized 8- to 9-inch lifts.

All of the soil-cement was specified to have either 12 or 14 percent cement (by dry weight of the soil). The percent cement was based on minimum compressive strength requirements of

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600 lb/in^2 at 7 days and 875 lb/in^2 at 28 days or durability losses of 6 percent maximum for wet-dry tests and 8 percent maximum for freeze-thaw tests.

For all of the features, the compressive strengths of specimens prepared during construction and of record cores from the facings exceeded the design values. The percent compaction averaged 98 percent or more of the maximum laboratory dry density as determined by the USBR compaction test. Details for some of the projects have been given by DeGroot (1971) and by Davis, et al. (1973).

MERRITT DAM

Merritt Dam is an earth dam located on the Snake River about 25 miles southwest of Valentine, Nebraska. The dam has a crest length of 3,222 feet and a maximum height of 126 feet above the valley floor. Construction of Merritt Dam started in 1961 and water storage began in 1964. Merritt Dam supplies water to the Ainsworth Canal which transports the water to the Ainsworth Irrigation District.

Merritt Dam was the first USBR dam where the contractor selected soil-cement as an alternative to riprap for upstream slope protection. Approximately 51,000 yd^3 of soil-cement were placed on the upstream face (4:1 slope) of the dam embankment in the fall of 1963. An asphalt-emulsion penetration treatment was also used for upstream slope protection on the 10:1 slope on the right abutment of the dam. By November of 1965, the asphalt slope protection had deteriorated significantly, and in 1968, the asphalt was replaced with soil-cement.

The soil-cement for the 4:1 slope was mixed in a continuous mixing stationary plant using a twin-screw pugmill. The soil-cement was hauled to the placement site in trucks, spread in a loose 8- to 9-inch layer, and then compacted with six passes from a sheepsfoot roller and four passes from a pneumatic rubber-tired roller. The exposed slope was coated with an RS-1 asphalt emulsion. The specifications required that the soil-cement be compacted to a lift thickness of approximately 6 inches and a lift width of 8 feet. Each soil-cement lift was offset 2 feet toward the dam centerline so that a minimum soil-cement thickness of 2 feet normal to the slope was obtained. A silty, fine sand and an average cement content of 14 percent was used for the mixture. The resulting densities of the soil-cement averaged 102.3 percent compaction with a standard deviation of 2.0; the average moisture was 0.3 percentage point dry of optimum with a standard deviation of 0.7 percent.

In October of 1968, the asphalt mat on the 10:1 slope was replaced with soil-cement. The soil-cement was mixed in a stationary mixing plant, and the mixture was then hauled to the placement site. The soil-cement was placed in two 6-inch lifts parallel to the slope of the dam embankment starting at the bottom of the embankment and adjacent to the existing 4:1 soil-cement slope protection. This resulted in a smooth pattern instead of the stair-step pattern previously used. The soil-cement was laid down in a strip and then compacted to about 1.5 feet from the edge of the strip. The next strip was then spread and the uncompacted portion was then compacted with the adjacent strip. Thus, the compaction operation resulted in joints only at the end of the strip and at the end of the day's run. The soil-cement was compacted by eight passes with a pneumatic roller. Placement moistures were maintained at 1 to 2 percentage points dry of optimum to prevent excessive rutting of the soil-cement. The first lift was cleaned with a power broom before placement of the overlying lift. The soil-cement was covered with a moist soil cover to aid in curing.

The First 10 Years After Placement

An inspection of the soil-cement slope protection 3 years after construction indicated that the slope protection was in excellent condition with only minor wearing and breakage. At that time, the most severe conditions at the damsite were 60 to 70 m/h winds from the northwest, resulting in 4- to 5-foot waves. The caretaker of the dam stated that 4- to 5-foot waves breaking onto the dam facing is common during storms.

The first notable damage to the soil-cement slope protection was observed during an inspection in September of 1973. A 6- by 10-foot section of soil-cement had been significantly damaged. At that time, a program was initiated to monitor the erosion of the soil-cement annually.

1979 Assessment of Damage

By 1979, the soil-cement slope protection over the entire length of the 4:1 slope had deteriorated; however, the most significant damage occurred on the left side. At approximately 300 feet from the left abutment, sections of the soil-cement lifts 30 to 40 feet long and 3 feet wide were removed. This extensive damage was attributed to ice forming between unbonded soil-cement lifts, and severe wave action. Ice formation between lifts causes the soil-cement to crack, and the broken pieces are then removed by wave action.

The soil-cement on the 10:1 slope remained in good condition; however, there were construction joints occurring at approximately 300-foot intervals. At some of these construction joints there is an overlapping displacement. This displacement may have been caused by freeze-thaw action and temperature stresses, rather than wave action.

In October of 1980, USBR personnel initiated a sampling and testing program to determine the thickness of the soil-cement slope protection on the 10:1 and 4:1 slopes, and to determine the cause of the uplift of the soil-cement on the 10:1 slope at the vertical construction joints. Compressive strength, wet-dry durability, and freeze-thaw durability tests were performed.

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Results of the coring indicated that the thickness of the remaining soil-cement slope protection on the 10:1 slope ranged from 13.0 to 16.5 inches. The specifications called for a thickness of 12 inches. The soil-cement slope protection on the 4:1 slope varied in thickness from 8.5 to 26.8 inches. The specifications called for a minimum thickness of 24 inches. Repair was necessary in the severely damaged areas.

The average compressive strength of the 16 cored specimens tested was 3,623 lb/in^2. The record cores during construction had an average strength of 930 lb/in^2. The percent loss after wet-dry durability testing was less than 1 percent for all cored test specimens. The percent loss following results of the freeze-thaw durability testing was 1 percent for all cored test specimens. Laboratory testing indicates that the soil-cement on both slopes is of good quality. The severe damage on the 4:1 slope appears to be due to the lack of bonding between lifts and temperature stresses caused by the extreme weather conditions.

The cause of the uplift of the 10:1 soil-cement slope is sand filling the construction joints. The sand-filled vertical construction joints cause the slope protection to uplift when the soil-cement expands during the summer.

Repair of the Damage

In the fall of 1980, repair of the soil-cement on the 4:1 slope was begun. The repair consists of placing an overlay of a four-sack mix of lean concrete over the soil-cement surface from elevation 2948, down the slope about 20 feet. The lean concrete was tied into the existing facing with reinforcement bars. This type of repair is planned for almost the entire length of the soil-cement facing and covers the elevation range of the water level fluctuation. The repair will cover the severely damaged area and will protect the facing from future damage. Ice forming between the unbonded lifts of soil-cement is a major problem. Since lean concrete will cover the soil-cement, ice will be unable to form between the lifts, thus preventing future damage. Repairs will be performed over 3 years. In the fall of 1980, approximately 150 yd^3 of lean concrete was placed at a cost of $10,000. Another 123 yd^3 of lean concrete was placed in 1983 at a cost of $8,000. The remaining repairs will be performed in 1984.

The vertical displacement of the soil-cement on the 10:1 slope is a minor problem and should not impair the slope protection. There are no plans for repairs in this area.

CHENEY DAM

Cheney Dam is an earth dam about 25 miles west of Wichita, Kansas. It has a crest length of 24,500 feet and a height of 86 feet above river bottom. Construction was completed in 1964. The dam was built by the USBR to provide a municipal water supply for Wichita.

The 180,000 yd^3 of soil-cement for the upstream slope protection was constructed between April and October of 1964. The construction operation was identical to that used at Merritt Dam with one exception. The specifications required an 8-foot horizontal width for the compacted lift, and a 1:8 slope of the lifts toward the reservoir was used to provide a 10-foot width for ease in placement. The resulting densities of the soil-cement averaged 98.7 percent compaction with a standard deviation of 1.8; the average moisture was 0.3 percentage point dry of optimum with a standard deviation of 0.7 percent.

1966 Damage

The first recorded damage occurred during a storm period of March 3-5, 1966. The water elevation was 1415 and the soil-cement was damaged from about elevation 1413 to 1415. The wind direction was primarily from the northwest, the average speed ranged from 10.5 to 17.5 m/h over the 3 days, and the fastest mile (observed over 1 minute) was 31 to 62 m/h. The riprap placed around the spillway structure was completely removed by the storm as well as 18 inches of the clay embankment beneath the riprap. In several areas between stations 50 and 125, the soil-cement lifts had broken back about 2-3 feet from the edge of the lift. At eight locations, the breakage was considered extensive enough to be measured and photographed for future observation. The worst area was at station 85+75, where portions of three lifts had been broken off and washed away so the lift at the bottom of the breakout was exposed for a width of 5 feet over a length of 35 feet.

The riprap was replaced with larger pieces. A survey showed that the soil-cement was originally overbuilt enough so that, in the damaged areas, the required normal thickness o soil-cement remained.

1970 Repairs

By 1970, four areas had broken back enough that the city of Wichita patched them by grouting in rebars into the existing soil-cement and filling the space with transit-mix concrete. These areas were not the areas noted for observation after the 1966 storm. The damage was between elevations 1419 and 1422; normal water surface had been about 1422.

1971 Damage and Repairs

On March 18, 1971, a severe windstorm occurred in the Wichita area. The wind direction was from the northwest; the fastest mile was 57 m/h and the maximum gust (instantaneous speed) was 82 m/h. Waves on the dam were reported by the dam tender to be 15 feet high. Calculations showed that the waves should have been about 7 to 8 feet. However, where the earth ramps had been left in place, there were no remains of the ramps below 8 feet above the water surface at the time of the storm. Spray from the waves iced up windshields of automobiles on the road a few hundred feet on the downstream side of the dam.

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The water surface at the time of the storm was at elevation 1421.4. The damage occurred between elevations 1415 and 1420. Damage was severe between stations 60 and 110. A total of about 300 linear feet of the clay embankment was exposed at three different locations between stations 95 and 105. A total of about 600 linear feet in three locations between stations 80 and 95 had only two lifts of soil-cement remaining. Figures 1, 2, and 3 illustrate some of the damage.

Figure 1. - Damage to soil-cement at Cheney Dam.

Figure 2. - View of most severely damaged soil-cement at Cheney Dam.

Figure 3. - Exposed embankment behind soil-cement at Cheney Dam.

The patches placed in 1970 remained intact. The riprap replaced around the spillway structure was not disturbed.

Repairs required about 1,100 yd^3 of lean concrete at a cost of about $34,500. The procedure was similar to the 1970 repairs using rebars grouted into place and transit-mix concrete.

1981 Repairs

In 1981 about 800 yd^3 of concrete was used to patch several locations where the soil-cement had broken away since 1971. The cost was about $56,000. No unusually severe storms had occurred; the damage appeared to be from normal wear.

A survey and drilling program was conducted in 1980 to evaluate the thickness of soil-cement remaining in some of the broken away areas. At eight sites, the soil-cement was thicker than 18 inches (limit of drill). At three sites, the thickness remaining was determined to be 13, 17, and 7 inches.

LUBBOCK REGULATING RESERVOIR

Lubbock Regulating Reservoir is near Lubbock, Texas, and is part of the Canadian River Project which delivers water from Sanford Dam to several cities in the Texas Panhandle. The reservoir was formed with compacted earth embankment up to 20 feet high that completely surrounded the reservoir area of about 40 acres. The soil-cement facing on the interior 3:1 slope was 2.5 feet thick normal to the slope, and there was a single 6-inch layer of soil-cement placed on the bottom of the reservoir. Construction was similar to Merritt and Cheney and was finished in 1966.

The soil-cement had 12 percent cement by dry weight. The dry density averaged 100 percent compaction and the moisture content averaged 0.3 percentage point dry of optimum.

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Although the magnitude of the waves is not as severe as at Merritt and Cheney, enough damage has occurred that repairs are considered necessary. The southeast corner has the most damage, but all four sides with the soil-cement will require some repair.

EVALUATION OF PERFORMANCE

The cost of repairs to date for Cheney and Merritt is far less than the cost savings realized (compared to the bids for riprap for each dam). In addition, the repair cost may be less than if riprap had been utilized. Many dams in the mid-West have required extensive repair of the original riprap. However, an economical solution to preventing extensive repairs should be considered. In the case of major damage, such as at Cheney Dam, adequate protection for the embankment behind the soil-cement must be a design consideration for embankments that may be susceptible to erosion. The USBR is continuing to evaluate the performance of Merritt and Cheney and considering possible improvements in the construction techniques used in soil-cement slope protection. In areas where severe wave action can occur, bonding together of the soil-cement lifts is being evaluated and considered. One test section of bonded lifts was incorporated into one of the dam facings and another test section is being planned.

Bonding of Lifts

The bond between soil-cement layers is generally weak. As a result, when the stresses created due to severe wave action are considered, the soil-cement facing may be thought of as a series of horizontal slabs stacked on the slope of the embankment as shown in figure 4.

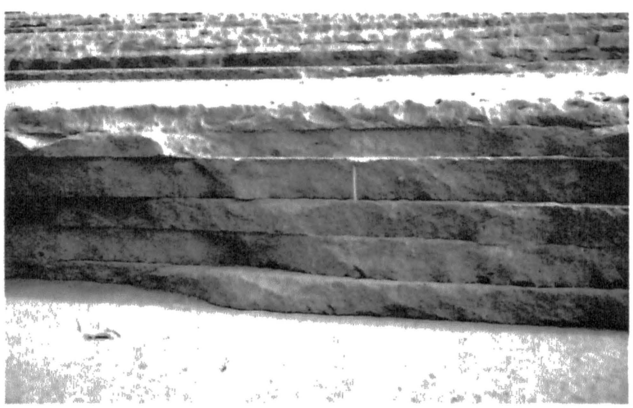

Figure 4. - Lifts of soil-cement shown at back of break-out.

If the exposed portion of the slab acts as a cantilevered beam during strong wave action, the low tensile strength of the soil-cement would result in a vertical crack. Combined with the vertical shrinkage cracks, smaller slabs are created that can be washed away. As each exposed portion is cracked and washed away, the layer below it has an additional exposed portion. The process can continue until the soil-cement has been completely removed as happened at a few locations at Cheney Dam.

The shrinkage cracks cannot be prevented, but bonding the layers together would create more massive sections of soil-cement that will not wash away and would protect the underlying layers.

Data on the bonding between the soil-cement lifts have been collected from some of the record coring and followup inspections of the soil-cement after construction.

The percent of the recovered lifts that have been bonded has ranged from 0 to about 50 percent. There is probably some degree of bonding between all the lifts but not enough to survive the coring operation. The results of direct shear tests have shown that the strength of some of the recovered bonds can be almost as high as that of the intact soil-cement. However, some of the recovered bonded lifts separated during handling or transit. The percent of bonded lifts recovered depends on two factors: (1) the original bond strength that was created between the lifts, and (2) the variations in the coring operations.

As reported by DeGroot (1976), laboratory tests have shown that the original bond created between the lifts depends on the time delay between lift placement, the frequency of moisture being added to the lift surface, the available moisture during curing, and the surface texture. The time delay has a much greater effect on the bond strength than the other variables. In field coring operations, it has been observed that in specific areas known to have less than 2-3 hours delay between lift placements, the recovery of bonded lifts has been almost 100 percent. However, for most of the field coring data, the time delay between specific lift placement is not known. The age of the soil-cement also affects the percent of bonded lifts recovered. In the same way that the compressive strength of the soil-cement has been shown to increase with time, the strength of the bond should also increase.

The percent of bonded lifts recovered also depends on the coring operation. The type and condition of the drilling equipment and the care taken during drilling can create varying amounts of shear stress on the bonded lift. The size of the core has been shown to be a significant factor. For one coring investigation, two different core barrel diameters were used for companion holes at various locations on the facing. For a 3-inch core, 29 percent of the recovered lifts were bonded together, and for a 4-inch core, 47 percent were recovered as bonded. The ratio of recovery between the two sizes is about the same as the ratio of the cross-sectional areas of the cores.

Bonding of the lifts appears to be the most critical factor in ensuring adequate performance of soil-cement slope protection. High-quality soil-cement does not necessarily

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ensure long-term durability. High compressive strength and low durability loss do not seem to be related to the ability of the soil-cement to withstand the uplift forces caused by severe wave action and ice buildup on the unbonded layers.

SOIL CEMENT BONDING STUDIES

USBR specifications for upstream soil-cement slope protection require that prior to placement of the overlying lift, the soil-cement be kept moist and the surface cleaned with a power broom to increase the roughness of the surface, thus providing a mechanical bond between lifts. Direct shear tests indicate that a stronger bond can be formed by application of cement between the layers of soil-cement.

In 1980, in an experiment to improve the method of bonding lifts together, a test section was constructed as part of the overall slope protection at Palmetto Bend Dam in Texas. The purpose of the test section was to evaluate the effectiveness of applying a bonding agent (cement slurry) between layers of soil-cement. The test section was 600 feet long, and located between stations 182+00 and 188+00 and elevations 41 and 47 feet. Five hundred feet of the test section consisted of a broomed surface with cement slurry applied between lifts. The remaining 100 feet of the test section was only broomed.

The water/cement ratio of the slurry ranged from 0.71 to 0.80 (average of 0.72) with application rates (pounds of dry cement/yd^2 of soil-cement) varying between 0.73 and 1.13 (average of 0.89). The slurry was mixed in 55-gal drums and sprayed onto the soil-cement with a gardenhose-type nozzle immediately prior to placement of the next lift.

Initial results of the test section have been very encouraging. Results of coring operations showed that many of the lifts in the slurry-treated portion of the test section were bonded together. No bonded lifts were recovered in cores taken outside of the slurry-treated portion of the test section.

Another soil-cement test section is planned for Calamus Dam, presently under construction. Calamus Dam is located about 5-1/2 miles northwest of Burwell, Nebraska, on the Calamus River. The test section will be incorporated into the soil-cement slope protection. The soil-cement facing at Calamus Dam will experience more severe wave action than the facing at Palmetto Bend Dam. In addition, the soil-cement at Calamus Dam will undergo freeze-thaw cycles. The 5,000-foot-long test section will be located between stations 19+00 and 69+00 and from elevations 2230 to 2250. This is the location where the maximum wave action is expected to occur.

The material to be used for the surface treatment will be portland cement applied both dry and in a slurry. The cement slurry will be applied between soil-cement lifts from stations 19+00 to 44+00. Dry cement will be used from stations 44+00 to 69+00. The water/cement ratio of the slurry will be 0.70. The application rates for both the cement slurry and dry cement will be 1 pound dry cement per 1 yd^2 of soil-cement.

The test section will provide information on: (1) the additional costs of bonding lifts together, (2) the techniques contractors might use to apply dry cement and slurry, (3) evaluation of construction control techniques, and (4) the performance of dry cement and slurry bonded soil-cement under severe environmental conditions. The test section will be evaluated by periodic inspections and an extensive coring and laboratory testing program. Laboratory testing will consist of direct shear, unconfined compression, and water loss tests to evaluate the effect of curing time on shear strength and the permeability of the bonded joints. A comparison will be made of the number of bonded lifts in the test section to the number of bonded lifts in the untreated soil-cement.

SUMMARY AND CONCLUSIONS

The soil-cement upstream slope protection on three USBR embankments built in the 1960's has been damaged enough to require repair. Although repair cost is less than the cost savings realized during construction and probably less than if riprap had been used, the USBR is studying methods of preventing such damage. Laboratory and field test sections indicate that bonding the soil-cement lifts together may prevent major damage due to severe wave action on the soil-cement facing. An extensive test section utilizing lift bonding is planned for a dam currently under construction.

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