Construction of Stair-Stepped Soil-Cement Bank Protection

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Abstract: Along normally dry rivers in the arid southwestern United States soil-cement has become a popular method of protecting banks and bridge abutments from erosion and collapse during floods. This paper focuses on construction of soil-cement bank protection. Construction topics discussed include control of water, central mixing plants, and the equipment needed to transport, spread, compact and cure soil-cement built in stair-stepped fashion on relatively steep riverbanks. Additionally the materials, mixture proportions and section dimensions of soil-cement bank protection, are discussed. Production rates and cost factors are also presented.

INTRODUCTION

The erosion of sand stream banks is a severe problem when there are flood flows in rivers passing through urban areas such as Tucson, Phoenix, and Albuquerque in the arid southwestern United States. During the October 1983 flood at Tucson, unstabilized banks on the Santa Cruz river eroded as far back as 469 ft (140 m) from their pre-flood locations. Figure 1 shows the collapse of the end span of the northbound lane of the Interstate 19 bridge, which is located just south of Tucson. In the background it is seen that the entire bridge on the road leading to the San Xavier Indian Reservation has been washed away. The left sand abutment eroded back several hundred feet to the position shown in the photograph. The abutments at both ends of the Interstate Highway Bridge are now protected with soil-cement bank protection.

The prime method for addressing this problem is the use of cement-stabilized on-site sand, known as soil-cement. This cement-stabilized natural material protects banks and is used to protect grade control structures in these areas.

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The design and construction of soil-cement bank protection is similar to soil-cement slope protection for new earth dams and other embankments. There are differences however, particularly the issue of water control and the steep slope of the embankment to be protected. Both designs involve placing horizontal layers of soil-cement in a stair-step fashion up an embankment slope. Bank protection slopes are typically steeper than those of earth dams. Current designs for the upstream slopes of new embankment dams tend to be about 3.0H:IV. Slopes of 1.0H to 1.0V for soil-cement bank protection conform to the near vertical slopes of the native banks. Such steep slopes minimize right-of-way requirements and increase the hydraulic efficiency of the cross section of the channel.

FIG. 1. Eroded sand banks and damaged bridges on the Santa Cruz River south of Tucson, Arizona.

CONTROL OF WATER

It is very seldom that ground or flowing water is encountered in the construction of soil-cement slope protection for a new earth dam because the water from the river or stream is diverted in some manner around the construction site. Most soil-cement bank protection is constructed during dry seasons where there is no or hardly any flow in the waterway. However, unexpected rains or effluent from a sewage treatment plant can cause flowing water in the stream. In these cases, the contractor must either wait for the river to gradually recede or the water can be diverted using dikes placed adjacent to where the soil-cement will be placed. In some cases, water stored in a natural bank is released when the bank is excavated in preparation for placing the soil-cement protection. This water may be drained with a gravel drainage layer placed adjacent to the slope and below the first soil-cement layer. In order to properly construct the soil-cement traditional dewatering methods can also be employed. Section Dimensions

The most economical construction method of soil-cement bank protection is by using conventional highway construction equipment. This is because contractors already have the necessary equipment and do not have to make capital investments that can be employed only for a limited amount of work. This economic consideration manifests that the construction process determines the minimum thickness of protection. Compacted layer thicknesses have generally ranged from six to nine inches (150 to 230 mm) with eight to nine inches (200 to 230 mm) becoming more common on recent projects. Then, considering a minimum width of eight feet (2.4 m) needed for haul trucks with an eight-inch (200 mm) layer thickness, the minimum thickness measured perpendicular to the slope calculates to be about 5.2 feet for a 1.0H:1.0V slope and 3.9 feet for a 1.5H:1.0V slope of the bank protection. See Figure 2 for the typical section of a soil-cement bank protection constructed at Tucson, AZ.

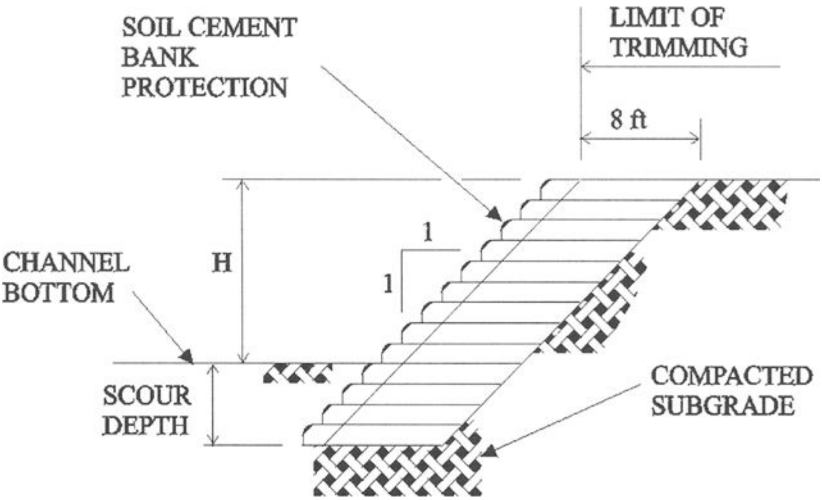

FIG. 2. Typical Bank Protection Section at Tucson, Arizona.

The elevation of the top of bank protection and the toe elevation can be computed from hydraulic and geomorphic considerations. The main factor in determining the crest elevation is the level of protection desired. This level is usually based on the 1 in 100 year flood, but some early designs in Tucson, AZ., were built to accommodate the 1 in 25 year flood. In the latter case when a flood occurred in excess of the 1 in 25 year event at Tucson in 1983, the soil-cement still performed well. When this higher flow occurred, the bank protection section was overtopped and there was erosion of soil from behind the soil-cement. Still, the erosion resistant soil-cement remained intact and in place. Following the flood, compacted fill was placed in the eroded areas and the bank protection was ready to withstand the next flood event.

Other factors to consider in establishing the elevation for the top of section are freeboard and the influence of debris, water and sand movement, and super elevation at bends.

The toe elevation for the soil-cement bank protection should be based on the many scour components computed for a 100-year event. While it is relatively easy to extend soil-cement bank protection upward, it is obviously more difficult and costly to place the toe deeper.

MATERIALS AND MIXTURE PROPORTIONS

Soil-cement is generally produced by using on-site soils that are mixed with portland cement (Type II), and water. Sand or sand-gravel for soil-cement usually comes from the banks or sandbars in the river to be protected.

Materials

Well-graded sands or sand gravel mixtures require the least amount of cement to provide adequate durability to resist deterioration due to weather or river flows. The gradation of these bank materials can vary depending upon location, but little processing of the river-run material is required. At most sites, the only processing required is to scalp off oversize clods, roots, or rocks on a 1½" (38mm) screen. However, material from the Salt River at Phoenix contains many large cobbles. In such a case, all material greater than three inches (75 mm) needs to be screened out. Additionally clay or calcareous cemented balls greater than one inch (25 mm) in size should be screened out and wasted.

To assure that the mixture can be properly compacted a minimum of 40% of the soil-aggregate should pass the #4 (5 mm) sieve. The amount of fires used in soil-cement bank protection projects has ranged from 3% to 20%. Clays with a plasticity index (PI) greater than six are generally not allowed, as they require a greater amount of cement for equivalent durability. Additionally it is more difficult to mix the clay and cement.

Mixture Proportions

With minimally processed on-site soil, standard laboratory tests on mixtures of soil plus cement are used to determine the three fundamental requirements for durable soil-cement (1) proper moisture content (2) adequate cement content and (3) adequate density

1. Moisture Content – the "standard" Proctor moisture density test (ASTM D558) is used in the laboratory to determine optimum moisture content and maximum density for the soil-cement mixture. The results of the test are used during construction to determine the amount of water to be added to the soil and the target density for the compacted soil-cement mixture.
2. Cement Content – the amount of cement specified is the minimum required to produce a material that will resist volume changes produced by external

variations in moisture (wetting and drying) and temperature (freezing and thawing). This amount of cement can be determined either by utilizing the results of laboratory durability tests (wet-dry and/or freeze-thaw) or by achieving a minimum seven-day compressive strength that correlates to a high level of confidence that the compacted mixture will be durable (commonly 600 psi (4.14 mpa)). For special conditions such as those encountered at Phoenix, AZ where coarser river sediments have greater erosion potential, a higher minimum seven-day compressive strength is specified (750 psi (5.17 Mpa)). Actual cement contents used for soil-cement bank protection have ranged from 7 to 12% by dry weight of soil.

3. Density – High density directly correlates to high compressive strength and therefore high erosion resistance. A target density can be determined either in the laboratory using standard Proctor compactive effort or by a test strip using actual materials and equipment planned for use on the project. Then, some slightly lesser density, such as 98% of the target density is specified for construction.

CONSTRUCTION OPERATIONS

The basic construction process, after control of water and excavation of the slope to the toe elevation, consists of proportioning and mixing, transporting, spreading, compaction, finishing, and curing the soil-cement. Special construction features that may be involved with a project include treatment of the outer edges, bonding successive layers, and construction joints. As with most construction projects, proper selection and utilization of equipment is the key to success.

Proportioning and Mixing

Central mixing plants of the twin-shaft pugmill variety are commonly used for volumetric proportioning (as opposed to weigh batching) and mixing the soil-cement. These continuous mixing plants with rated capacities between 250 and 500 tons/hr are able to produce between 170 and 340 cy of soil-cement per hour. The plants are usually located atop the bank in an area adjacent to the sand aggregate source or where there is sufficient space for processing and stockpiling the soil. Location atop the bank insures that, the mixing plant will not be affected by flood flows in the river. However, some contractors have accepted the risk and set their plants in wide riverbeds such as the Salt River provides at Phoenix. Such an arrangement offers easy access to the work and an abundant supply of stabilization material.

Transporting

Plant mixed soil-cement is transported from the mixing plant either by rear dump trucks or by bottom dump trucks. When the latter larger capacity truck/trailer piece of equipment is used, a width greater than eight feet (2.4 m) may be required to accommodate these larger and wider trucks. In some cases, the contractor, at his expense, may elect to build a wider soil-cement section in order to achieve a higher production rate. Access to the placement area from a plant atop the bank is usually accomplished by sloping earth ramps. Soil-cement ramps are sometimes part of the design to allow egress in and out of the river bottom – mainly during a flood event.

On some projects, where the design provided for a narrower placement width or where the access situation precluded the use of truck transport, conveyor belts have been used to transport the soil-cement, Figure 3.

FIG. 3. Conveyor belt feeds soil-cement to spreader box, Rio Puerco, Gallup, New Mexico.

Spreading

When dump trucks are used, spreading of the soil-cement to a uniform loose thickness for compaction may involve the use of a dozer pushed spreader box. However, dozers or motor graders (Figure 4) are also used to spread the soil-cement mixture when it is placed in a "ribbon" by a bottom dump truck. Some contractors have used an 8 ft. (2.4 m) wide spreader attached to the rear of a motor grader with good results, in this latter case.

Placement of soil-cement lifts should be limited to a total height of 4 ft (1.2 m) in a single 8 to 10 hour construction shift. This limit helps prevent possible stability problems. Instability of the layered soil-cement mass as evidenced by bulging of the outer face can occur if too much soil-cement is placed before the lower layers have attained sufficient stability to properly support the weight of the material and equipment above.

Compaction

To achieve density a variety of wheeled rollers have been used to compact soil-cement. In the early development of soil-cement bank protection, rubber-tired (pneumatic) rollers were used. In recent years, steel wheel (single or double drum), Figure 4, or pad foot vibratory rollers have been used to compact soil-cement mixes that used granular soils. At times the vibratory roller creates narrow, closely spaced cracks transverse to the direction of travel. A rubber-tired roller may be required for final compaction to close these cracks or striations. Any piece of equipment that consistently produces the specified level of density should be allowed by the specifications.

FIG. 4. Steel wheel vibratory rollers compact soil-cement along Salt River at Phoenix, Arizona.

Finishing and Curing

If the depth for any compacted lift of soil-cement exceeds specification, the use of a grader may be required to trim the soil-cement surface. While this problem is better controlled in the spreading operation, any trimming of the compacted soil-cement surface should be accomplished soon after compaction, as the soil-cement hardens quickly. Soil-cement surfaces need to be kept clean and continuously moist until the next layer is spread. However, the surface should not be puddled with water.

Curing of the top surface and the outer exposed face of the soil-cement should be for a minimum of seven days and preferably 14 days. Curing by a continuous spray of water is best, but a moist earth blanket at least 6 in. (150 mm) thick can be used for the top surface. Concrete curing and bituminous sealing membranes are seldom effective due to the low water content in the soil-cement mixture. Cost and aesthetics are other factors that may rule out membranes to cure soil-cement bank protection.

Weather Considerations

Soil-cement should not be placed in cold weather when freezing temperatures are expected at night. Most specifications in the southwest require the air temperature to be at least 45°F (7°C) or 40°F (4°C) and rising at the time of placement. Where freezing temperatures are anticipated at night, previously placed soil-cement needs to be protected against disruption to cement hydration caused by freezing. Adequate protection to maintain the temperature of the soil-cement above freezing can be achieved by covering the soil-cement with insulating blankets. Other protective methods, such as earth cover or straw, may be effective on the top surface, but cannot properly protect the sides of the steep soil-cement section.

SPECIAL CONSTRUCTION FEATURES

Construction joints

When soil-cement construction is interrupted, such as at the end of each day's placement or due to equipment breakdown, a full depth vertical construction-joint should be made. The vertical joint can be produced by cutting back into the fully compacted soil-cement lift to produce a vertical face perpendicular to the direction of layer placement. The loose material so cut should be wasted.

Bonding

Where there is a delay in placing the next layer within a specified time period or for some special design condition, bonding of successive layers may be required. The exposed layer should be kept clean and moist until grout or dry cement for bonding is applied. In either case, the bonding agent is applied just prior to placing the next layer of soil-cement and the preceding layer is not allowed to dry out. When dry cement is used for bonding, it should be applied at the rate of approximately 1 lb/sq.yd. (0.5 kg/m^2). The dry cement can be sprinkled with water prior to placing the next layer or activated by the water contained in the soil-cement mixture in the layer above.

One area where bonding is critical is between the uppermost two or three lifts for a soil-cement grade-control structure (drop structure). In this manner, improved shear values are obtained by achieving greater cohesion in an area where there is little weight above to mobilize shear-friction resistance.

Outer edges

The outer edges of soil-cement bank protection can either be:

1. Left ragged as is.
2. Trimmed to form a smooth slope, Figure 5.
3. Trimmed or compacted to produce definite stair-steps, Figure 6.

A smooth plane improves hydraulic properties during a flood. A wing blade attached to a dozer accomplishes the trimming. This should be done soon after final compaction. Waiting more than one day makes the trimming of hardened soil-cement more difficult.

FIG. 5. Smooth trimmed soil-cement bank protection, Rillito River at Tucson, Arizona.

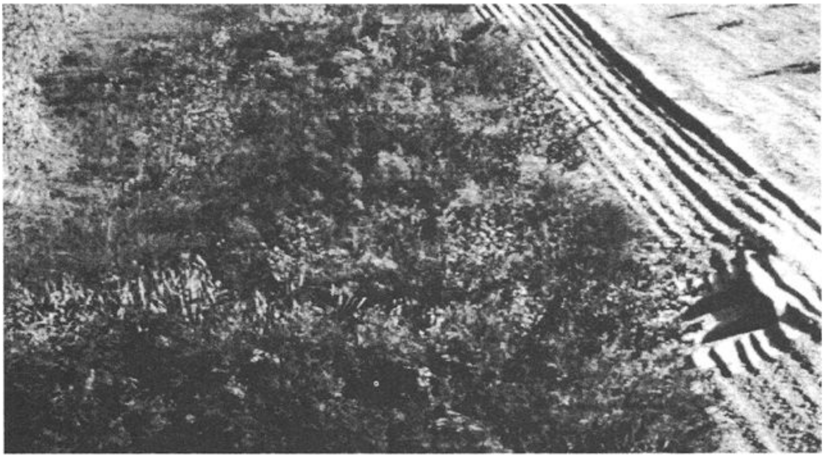

FIG. 6. Stair-stepped soil-cement bank protection, Sand Creek, Aurora, Colorado.

Definite stair-steps are desired in some areas to allow people and animals to climb out from the river bottom during flash floods. Stepped edges, that can be quite attractive, are invariably associated with slopes flatter than 1.0 H: 1.0.V. Contractors have devised many methods to cut, form or compact the outer edge of a soil-cement bank to produce a stair-stepped effect. It is desirable to have the exposed outer edge well compacted to a high density. This is an area where durability is most needed. Figure 7 shows a grade control structure on a small waterway near Albuquerque, NM. Definite steps were produced by overbuilding and cutting back to form an aesthetically pleasing vertical surface.

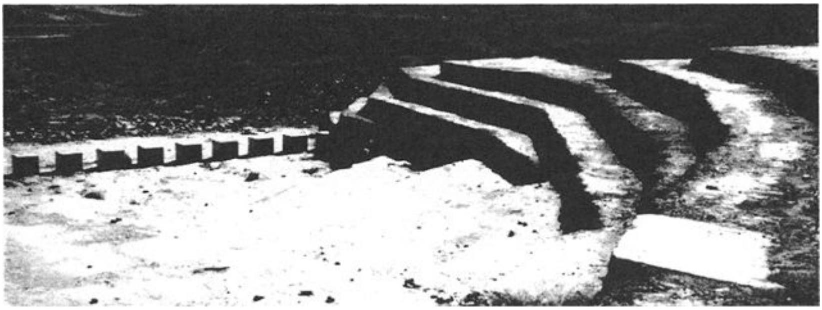

FIG. 7. Cut steps on soil-cement drop structure on La Barranca Arroyo near Albuquerque, New Mexico.

COST

The in-place cost of soil-cement bank protection can be divided into two components: 1) the cost of cement and 2) the cost of producing the soil-cement. The cost of cement includes the delivered cost of the portland cement, plus the cost of on-site storage. The costs associated with producing the soil-cement basically consist of all construction related items except the cement. These include the sand aggregate as well as proportioning, mixing, transporting, spreading, compacting, trimming and curing the soil-cement.

The cost of cement is hardly affected by the size of the project (i.e. volume of soil-cement). However, the cost of producing soil-cement is quite volume dependent and involves many factors. Invariably, the cost of producing soil-cement decreases as the volume to be placed increases. Factors affecting the production cost include:

1. Availability and haul of aggregate,
2. Ease of construction,
3. Specifications, and
4. Competition.

Obviously, low bid prices for soil-cement are obtained when aggregate is located on-site and requires little haul or processing. Other factors tending to reduce cost are: good access between the mixing plant and placement area, little need to control water at the site, projects having large volumes of soil-cement and a reasonable number of experienced bidders.