Soil-Cement *Solutions*

SOIL-CEMENT FOR WATER RESOURCES APPLICATIONS

Compacting sloping soil-cement step face with vibratory plate compactor.

Upstream Slope Protection Repair

JACKSON LAKE RESERVOIR DAM
MORGAN COUNTY, COLORADO

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Jackson Lake Reservoir Dam was constructed about 100 years ago as an off-channel reservoir for storage of irrigation water. The dam embankment is approximately 2 miles (3.2 km) in length with a structural height on the order of 20 feet (6 m) and a maximum storage capacity of 35,000 acre-feet (4.3 x $10^7 m^3$). The upstream slope protection consists of one to three layers of concrete slabs constructed around 1912. The embankment consists of homogeneous, very loose to loose, fine to medium grained, clean to silty and clayey sand placed over foundation consisting of similar soil. Waves up to 8 feet (2.4 m) high damaged the concrete slabs and eroded the crest and downstream slope resulting in piping of the embankment soils and voids (sinkholes) in the crest and below the concrete.

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PCA Portland Cement Association

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Studies were conducted to determine the cause of sinkhole development and failure of the concrete slabs. Studies concluded that the vast majority of voids were located in areas where the toes of the concrete slabs were above the adjacent beach. The fluctuation of hydrostatic pressure transmitted to the embankment through wave action caused a pumping action that resulted in the piping of the fine granular soil from the embankment along the upstream toe, and also through occasional open joints and holes in the concrete slabs. It was concluded that any rehabilitation should include construction of a cutoff below the existing beach. Building up the beach had been performed previously with on-site soils, but the lake would wash away the fine granular soil and return the beach to its original state.

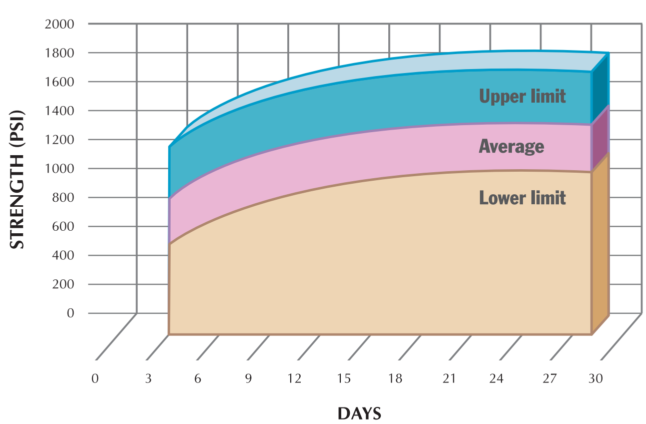
Several rehabilitation alternatives were considered. These included flattening the upstream slope to a stable beach slope and providing gravel armor or riprap armor, installing a completely new concrete slope protection, or overlaying the existing concrete upstream slope with soil-cement. The study concluded that the most cost-effective rehabilitation approach was the use of soil-cement due to the availability of adequate fine, clean to silty sand on the beach.

The soil-cement mix design was conducted on aggregate samples obtained from approximately 150 pits taken along the 2-mile (3.2-km) long embankment. The suitable aggregate material consisted of non-plastic, clean to silty sand with an ASTM soil classification of SP to SM and AASHTO classification of A-2 and A-3. The results of laboratory testing indicated that soil-cement met PCA criteria at 7% cement and USBR criteria at 8% cement. Based on the large area and anticipated variability of the aggregate, an additional 2.5% cement was recommended for a design cement content of 10.5%.

Rehabilitation consisted of constructing a cutoff extending 3 to 5 feet (1 to 1.5 m) below the

Soil-cement placement operations adjacent to existing concrete parapet at crest of dam.

Summary of Compressive Strength Testing of Soil-Cement Samples



existing beach or toe of the concrete facing. Literature had indicated a minimum soil-cement bench width of 8.5 feet (2.6 m) is determined by the trucks delivering the product. This would have limited the length and/or height of the rehabilitated section due to budget constraints. Prospective bidders indicated they would be able to place soil-cement at a narrower width of 6 feet (1.8 m). The specifications required the soil-cement be placed in 8-inch (200 mm) lifts and compacted to at least 98% of ASTM D 558.

ASI RCC was selected based on their low bid with 6-foot (1.8-m) placement width option. The contractor chose to use a batch plant to mix the soil-cement. However, during construction the fine sand caused binding of the mixing blades and slowed production. Soil-cement was hauled by trucks and dumped into a metal skip bucket. A large excavator retrieved the material from the skip bucket and placed it on the lift surface. A small dozer spread the soil-cement to the desired thickness and width, and compaction was achieved with a vibratory, smooth double-drum roller. A test section demonstrated that the contractor could place the soil-cement in 6-foot (1.8-m) widths and achieve specified compaction using 12-inch (300-mm) lifts with 4 to 5 passes of compaction equipment in vibratory mode. The excavator and skip bucket method easily kept up with the soil-cement produced by the batch plant.

Acceptance of work was based on testing the in-place density by nuclear gauge and performing unconfined compressive strength tests on compacted soil-cement specimens. Strength tests generally indicated the requirement of 600 psi (4.1 MPa) was obtained in 1 day and 800 psi (5.5 MPa) was obtained in 3 days. The in-place strength was confirmed by obtaining cores of the placed soil-cement. The test data summaries, and photographs were transmitted daily by e-mail, which afforded results concurrent with production summaries and work progress reports.

The project was completed in the specified time between September and December of 2001, and the filling of the reservoir began in January 2002 in preparation for the summer irrigation season.

Lessons learned from this project:

- **Granular embankments with inadequate upstream filter or cutoffs are subject to piping from wave action and fluctuation of hydrostatic pressure.**
- **The placement width of soil-cement layers is limited by compaction equipment rather than the size of truck delivering the product.**

Soil-cement batch plant located within drained reservoir.

Thin Soil-Cement Protection

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Soil-cement shown above at normal operating pool, following reservoir refilling.

Soil-cement placement completed in one cell prior to refilling.

Introduction

The Cedar Creek Balancing Reservoirs located in Kennedale, Texas, just south of Fort Worth, provide raw water supply storage for the Tarrant Regional Water District. The reservoirs were constructed in 1972 and 1978 of on-site clay material and lined with Hypalon. The side slopes of the reservoirs are three horizontal to one vertical and the outside slopes are grassed. The reservoirs share a common center embankment and access road that runs along the top of the embankments. Both reservoirs have a water surface elevation of 737 feet (224.6 m) msl and a top of embankment elevation of 740 feet (225.6 m) msl. The embankment of the east reservoir is 40 feet (12.2 m) high. The west reservoir is 10 feet (3 m) deeper than the east reservoir. The reservoirs have a total storage capacity of 324 million gallons (1.2 trillion liters).

Both reservoirs have experienced benching and erosion of the slopes. The problem was worse on the north slopes, where the prevailing southerly winds caused wave induced damage. A 4-inch (100-mm) layer of concrete slope protection was added to the north slopes of the reservoirs in the 1980s.

There were numerous areas where the liner had ripped, and benching of the slopes under the liner was obvious. The liner had served its intended function of impermeability with no apparent signs of seepage or leakage on the outside slopes of the reservoir. However, the erosion protection function of the liner had not worked as well. The Hypalon liner appeared to have reached the end of its useful life.

Design Considerations

Several options were evaluated and discussed with the Water District. The criteria used to evaluate each option included degree of impermeability, durability, and ability to provide erosion protection, as well as ease of maintenance. The options considered were chemical treatment of the in-place embankment material, high-density polyethylene (HDPE) liner, and the use of soil-cement. A soil-cement liner would assure durability, which would allow the use of equipment for future maintenance, but would likely crack, thereby increasing its permeability. One additional consideration was the use of an HDPE liner with a thin layer of soil-cement. This was utilized on a previous project designed by Freese and Nichols, and it would provide both the impermeability and durability required at a reasonable cost to the Water District. A 9-inch (24-mm) layer of soil-cement over 60-mil textured HDPE liner was recommended.

Construction

Bids for the project were opened in August 1999. The project was awarded to Eagle Construction and Environmental Services, Inc., of Eastland, Texas. The bid price was $2.7 million. The unit price for the 45,000 cubic yards (34,400 m^3) of soil-cement was $27.74 per cubic yard ($36.28 per m^3). The 172,000 square yards (143,790 m^2) of 60-mil textured HDPE liner was bid at a unit price of $2.99 per square yard ($3.58 per m^2).

Since the Water District could not meet its customers' demands with both reservoirs out of service, work could be performed on only one reservoir at a time. Construction began with the west reservoir. The original Hypalon liner and concrete slope protection were removed, and the slopes were regraded. The work included the construction of an access ramp to allow for future maintenance of the reservoir.

The earthen slopes and bottom of the reservoir were compacted to 98% of maximum density. The HDPE liner was placed on the slopes and across the bottom. Placement and testing of the liner progressed very quickly.

The project specifications for soil-cement required the use of an on-site pug mill, development of a mix design, calibration of the pug mill, a test section, compaction at 95% of maximum density at optimum moisture of –1% to +2% and a 60-minute time limit between mixing and final compaction. Mix designs ranging from 6% to 12% cement and 0% to 6% fly ash were tested. The contractor proposed using a blended fly ash and cement material and manufactured sand. The use of the manufactured sand simplified the process. The contractor was able to pre-purchase the sand, and since it was a manufactured product there were no problems with inconsistency or change in materials, which sometimes necessitates adjustment to the mix design during construction.

Soil-cement placement operation.

The blended cement and fly ash product, called HPC, has been manufactured since about 1994. The process blends Type I cement with Class F fly ash in the grinding process. As the clinker is ground into powder, the fly ash is added and ground with the cement creating a well-blended product. The process blends approximately 20% to 22% fly ash with the cement. This product meets the requirements for Type II and Type V cement. The manufactured sand was tested with an 11% mix of the HPC. This resulted in a mix of 8.7% cement and 2.3% fly ash. Test results indicated a 28-day strength of 1,800 psi (12.4 MPa) and a loss of less than 1% from 12 cycles of the freeze-thaw test, which was acceptable.

The staging of the soil-cement placement posed the next challenge. The access ramp was not lined in HDPE to permit access to the interior of the reservoir. Large, heavy equipment used in material placement would have damaged the liner.

After a portion of the reservoir bottom was covered with the HDPE liner, a thickened section of soil-cement was constructed on the liner at the toe of the slope. The soil-cement was thickened to overbuild the section, so if the equipment wore on the surface, there would still be the minimum thickness required. Soil-cement was dumped on the liner, and it was compacted and then used as a road to place the next section of soil-cement. The placement of a thin layer of soil-cement on the HDPE liner was a very labor-intensive operation. The roller compacted the soil-cement as close to the edge as possible as long as there was a minimum of 9 inches (230 mm). The loose, non-compacted soil-cement at the edge was trimmed to a vertical joint to the liner with hand shovels.

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Flood and Environmental Protection

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The Santa Clara River is one of the few remaining "natural" dry-rivers in Los Angeles County, and the community and environmental agencies are determined to keep it as "natural" as possible, while still providing appropriate flood protection for the area. Concerned about the lack of environmental sensitivity inherent to traditional methods of bank protection, the City of Santa Clarita and the project developer, Newhall Land and Farming Company, collaborated to investigate alternative methods of providing flood control for the residential and commercial Bridgeport development. Newhall turned to Pacific Advanced Civil Engineering, Inc. (PACE) and soil-cement technology for an innovative, environmentally sensitive, and cost-effective solution.

Soil-Cement Solution

PACE provided Newhall with bank stabilization design that provides adequate protection for the Bridgeport development and satisfies the environmental sensitivity necessary for construction within the Santa Clara River buffer. The lower level of bank protection design includes two levels of soil-cement connected by overbank grade control structures in a ladder-like framework, parallel to the river. The lower level offers scour and flood protection up to the 100-year storm event, while the upper level offers protection against the Los Angeles County Department of Public Works (LACDPW) Flood Control Division Capital Flood. The Capital Flood assesses the flows from the 1,640-square-mile (4,250-km^2) watershed including flow

View of completed bank stabilization. Soil-cement is buried beneath recreational trail and landscaping.

First lift of soil-cement being spread at elevation of maximum scour depth.

bulking as a result of a burnt watershed. The lower level of bank protection offers security from flows of approximately 35,000 cubic feet per second (1,000 m^3/sec), while the upper level provides protection from flows of 118,000 cfs (3,400 m^3/sec).

Both levels of bank protection are placed at a 1:1 slope and followed conventional soil-cement design and construction standards. Typical heights for the lower level range from 13 to 22 feet (4 to 6.7 m), while upper level heights are 7 to 19 feet (2.1 to 5.8 m). The project's soil-cement specifications called for a 7-day compressive strength of 750 psi (5.2 MPa). However, the actual 7-day average was in excess of 1,100 psi (7.6 MPa). Over 85,000 cubic yards (65,000 m^3) of soil-cement was placed to complete the bank protection along 10,500 linear feet (3,200 m) of the river. The cement content varied between 8% and 10%, based upon the variation in the base material. Construction costs for the soil-cement placement, including excavation, backfill, and finish grading, were between $300 and $400 per foot ($90 and $120 per m). Upon completion, most of the soil-cement bank protection was buried and the backfill stabilized by the revegetation of the disturbed overbank area.

The soil-cement bank stabilization along the Santa Clara River provides unique engineering and environmental benefits:

- Flood protection for the adjacent residential and commercial development
- Erosion protection within the river overbank area
- Elimination of costly, unsightly, and environmentally unfriendly bank protection systems that traditional design methods would require

Vibratory compactor shown compacting soil-cement lift.

Benefits for the Bridgeport Community

The bi-level soil-cement bank protection is a superior alternative to the concrete or rip-rap linings traditionally used along the Santa Clara River, providing unique benefits in terms of:

Safety The creation of a stabilized overbank area reduces flow depths and velocities at the river's edge, allowing improved public access into and out of the river in an emergency.

Flood conveyance The soil-cement bank stabilization system provides proven flood protection to convey the project design storm flows within the main river channel, while maintaining lower velocities in the overbank area, which will preserve vegetation.

Durability and maintenance Soil-cement is a highly durable and stable erosion protection system requiring minimal maintenance.

Environmental resource protection Soil-cement significantly reduces the amount of natural resources used in the construction process. With approximately 90% of soil-cement being on-site natural material, only 10% (cement) requires transport to the site. Reduced consumption of natural resources also reduces the amount of traffic, pollution, and overall "cost" to the environment associated with the soil-cement bank protection system. The bi-level bank design also results in less excavation and disturbance of the existing environmental resource area.

Recreational amenity The moderately sloped (approximately 6:1), stabilized river overbank area offers an enhanced area for revegetation and recreation, including an equestrian trail.

Aesthetics Soil-cement bank protection is 70% – 100% buried, which allows for minimal visual impact to the environment. Moreover, the natural embankment stabilization material (soil-cement) is 90% native

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Soil-Cement Solutions is published by the Public Works department of the Portland Cement Association. Direct comments, address changes, and subscription requests to:

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and will blend into the surrounding environment wherever and whenever exposure occurs.

A Victory for Bridgeport and the Environment

Soil-cement has proven itself to be a highly reliable, durable, and safe means of flood control protection. Bridgeport's use of it in an innovative, bi-level design is a viable alternative to more traditional bank protection systems, providing benefits in terms of safety, cost-effectiveness, and environmental sensitivity that concrete and riprap linings cannot match. Several single-level (typical) soil-cement bank protection projects have been completed along the Santa Clara River watershed area, successfully providing environmentally sensitive bank protection. Single-level or bi-level soil-cement design produces a win for environmental resources, the public, flood control agencies, and developers. As the Bridgeport project has shown, with the right planning and engineering, development and the environment can coexist in harmony.

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Since the slopes were over 120 feet (37 m) long, placement of the soil-cement on the slopes exceeded the allowable time between mixing and compaction if placed in one section from bottom to top. Placement on about a third of the slope at a time worked best. This allowed placement of a wider area, which helped with the lateral stability of the soil-cement while meeting the time limit.

During placement, wrinkles caused by heating of the liner in the Texas sun worked their way up the slope and were pulled out in the anchor trench at the top of the slope. The ramp was fashioned last using some of the techniques employed for the haul road. The east reservoir was constructed in a similar manner.

The placement method required some trial and error, particularly on the slopes. After the material was pushed into place with the dozer, a smooth wheel vibratory roller was used for compaction. Four passes of the roller were required: The first was made without the vibration of the roller, and was followed by three passes with vibration when moving up the slope, and no vibration for compaction when moving down. The result was a well-compacted, smooth surface.

Conclusion

The HDPE liner with thin soil-cement proved to be an economical solution for rehabilitating the Cedar Creek Balancing Reservoir embankments, providing not only a durable surface, but an impermeable liner. The placement of the soil-cement on the liner required significant planning and flexibility to handle construction issues associated with the HDPE liner/soil-cement system. The project advanced soil-cement construction techniques with an innovative and economical solution that could be implemented in the field.

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PL072.01