CONSTRUCTION OF A SOIL-CEMENT-BENTONITE SLURRY WALL FOR A LEVEE STRENGTHENING PROGRAM

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Abstract

The U. S. Army Corps of Engineers has recently implemented a levee-strengthening program along the banks of the American River in Sacramento, California. During the rainy season, the existing levee system protects major commercial and residential areas of this metropolitan area. One of the main components of this program is the construction of slurry walls through the existing levees to improve stability by preventing seepage through and beneath the levee. Since conventional soil-bentonite slurry walls have little shear strength which would jeopardize the stability of the existing levees, and cement-bentonite slurry walls are significantly more expensive, soil-cement-bentonite slurry walls are being utilized for this strengthening program.

This paper describes a case study on the design, construction and performance of an underground soil-cement-bentonite barrier wall, which was used to isolate river water seeping into the American River levee and its foundation soils. Challenges to barrier performance included achieving a maximum allowable hydraulic conductivity of $5 \times 10^{-7}$ cm/sec while having a minimum unconfined compressive strength of 15 psi. The barrier wall was constructed during the period August 29, 1998 to October 29, 1998 (9 weeks) in a residential area with severe space limitations. Four large excavators capable of excavating to maximum depth of 80 feet were used. In order to meet the tight schedule and performance requirements, the barrier wall backfill mix was designed to fulfill the specified 28-day hydraulic conductivity requirement after only seven days.

1.0 Introduction

The project is located at the north bank levee of the American River in Sacramento, California. A Soil-Cement-Bentonite slurry wall was constructed between Howe and Watt Avenues to a depth of seventy (70) feet. This Federal flood control project is part of the $68 million “Common Elements” component of the American River Project authorized by Congress in 1996. This Project involves the construction of a slurry wall in the center of approximately 19 miles of the existing north and south levees on the American River, and raising and strengthening a small portion of the Sacramento River levee along the Garden Highway in Natomas. The levee’s length between Howe and Watt Avenues is 8500 feet, and its average width at the crown is 21 feet. The levee crossed overhead power lines at two different locations with a minimum clearance of 20 feet. The slurry wall project map is shown in Figure 1.
2.0 Background and Existing Conditions

2.1 Background

During floods when the river level is high, water tends to seep through and under the levee. If the seepage is serious, boils may occur on the landside. If the seepage begins to carry some of the levee material with it, the levee will eventually collapse causing flooding.

A slurry wall is designed to reduce the seepage of water through and under the levee during flood stages when the river is high. This increases the stability of the levee, which in turn reduces the chance that the levee will fail.

2.2 Existing Conditions

The levee was constructed primarily of sandy to silty soils overlying the native ground surface. Beneath the levee, the borings encountered layers of sandy, silty, and clayey soil deposits of various thicknesses and at various depths. A gravel and cobbles layer was encountered underlying these deposits along most of this reach of the levee. The elevation and thickness of this gravel and cobbles layer varied along the reach of the levee. The locations of the top of the gravel and cobbles layer varied from a depth of five feet to a depth of 40 feet from the existing levee crown. The thickness of the gravel and cobbles layers ranges from about 5 to 30 feet and was absent in a few locations. Underlying the gravel and cobbles layer, the borings encountered clayey to sandy soil deposits to the maximum depth of the explorations. The gravel and cobbles layer beneath the levee is believed to have served as a "channel" for seepage flow toward the landside of the levee and caused seep and boil conditions on the landside ground surface. The design considers the construction of a slurry wall cutoff along the levee crest. A typical subsurface profile is shown in Figure 2.

Figure 2
Typical Subsurface Profile
2.3 Evaluation of Depth of Cutoff Wall Penetration

A series of steady-state groundwater flow and seepage analyses in the levee's transverse direction were carried out to assess the depth of the cutoff wall required to satisfy the minimum factor of the safety for the downstream side (land side) of the levee against an undesirable seepage condition. The factors of safety were evaluated against soil boils at the downstream toe of the levee for three cases, with and without the cutoff and with a partially penetrating cutoff. The safety factor against soil boils is defined as follows (USACE, 1997):

\[ i_{\text{critical}} = \frac{\gamma_s - \gamma_w}{\gamma_w} \]

\[ \text{Safety Factor} = \frac{i_{\text{critical}}}{i_{\text{upward}}} \]

where \( i_{\text{critical}} \) is the upward seepage gradient that would cause heaving of the soil, \( \gamma_s \) and \( \gamma_w \) are the unit weights for the saturated soil and water, respectively, and \( i_{\text{upward}} \) is the actual calculated upward seepage gradient.

The upward gradient \( (i_{\text{upward}}) \) is obtained from the seepage analysis. A minimum safety factor of 2.8 was used as the threshold value for the initiation of a soil boil condition (USACE, 1997). The analyses were carried out using the computer program SEEPW (Geo-Slope International, 1992). SEEPW is a two-dimensional finite element code for solving both saturated and unsaturated flow conditions through porous media.

The results of the steady-state seepage analyses showed:

- A complete cutoff of the highly pervious gravel and cobble layer is needed in all analyzed cross sections. The cutoff must be complete, i.e., penetrate completely through the gravel and cobble layer to a depth of seventy feet from the existing levee crown, and be seated in the underlying less pervious layer.
- This complete cutoff is needed for the 200,000 cfs flow as well as for the 150,000 cfs flow, to prevent excessive upward gradients near the landside toe of the levee.
- Guidance was also provided for end effects, i.e., potential for flow around the ends of a cutoff.

3.0 Construction Methods

3.1 Slurry Wall Description

Slurry walls are commonly used as subsurface barriers to lateral flow of groundwater and to water-borne pollutants. The major characteristics of slurry wall construction are the use of a bentonite and water slurry during excavation to support the excavation without the use of other lateral supports such as shoring. Slurry walls are built by excavating a narrow trench, which was 2.5 feet wide for this project, while pumping slurry into the trench and maintaining its level at or near the top of the trench during the excavation. Usually, the trench is extended deeper or keyed into an underlying acquiclude, to form a bottom seal. The acquiclude forms the impervious base, and the backfill, which for this project, is soil-cement-bentonite mixture forms the vertical groundwater barrier. For this project two acquicludes were encountered during construction. One acquiclude consisted of sandy silt with gravel (ML), and the other acquiclude consisted of clayey sand (SC). Both acquicludes were keyed three feet to a depth of seventy (70) feet.

Bentonite clay is a montmorillonite clay and the most common amendment in soil-bentonite, soil-cement-bentonite and cement-bentonite slurry walls. Bentonite has the ability
to swell as much as 20 times its volume upon contact with water. Sodium-cation bentonite from mines in Wyoming, U. S. A. is the highest quality bentonite and is available dried and bagged for commercial use. Typical bentonite contents in soil-bentonite backfill are in the range of 1 to 3% by dry weight of the soil are usually adequate to create a barrier with a hydraulic conductivity (or permeability) of $1 \times 10^{-7}$ cm/sec (D'Appolonia 1980).

The slurry trench construction method is a proven method to construct a barrier wall. The soil-bentonite trench technique has been in use in the United States for over 20 years. On projects where the material excavated from the trench is suitable for use as backfill, the soil-bentonite system can be economical because of the minimum amounts of materials required. After the trench has been excavated under a bentonite slurry, more slurry is mixed with the soil adjacent to the trench or at a remote location. A bulldozer and/or hydraulic excavator is/are used to work the materials to a smooth consistency, and it is then pushed into the trench so that the backfill slope displaces the bentonite slurry forward. Excavating and backfilling in phases make the operation continuous with relatively small quantities of new slurry required to key the trench fill and to mix backfill. Figure 3 shows the excavation and backfill procedures.

Due to potentially large hydraulic head and the little shear strength in soil-bentonite, the designer selected soil-cement-bentonite as backfill for the barrier wall. Also, soil-cement-bentonite provides greater erosion resistance should overtopping of the levee occur.

The greatest economy can be realized when the excavated soils can be reused in the backfill. For this project, the excavated soils were suitable for preparation of soil-cement-bentonite backfill, after removing the cobbles, and blending and composting fine and coarse materials.

### 3.2 Objective And Approach

Prior to construction activities a laboratory mix design was conducted to predict soil-cement-bentonite performance, and to determine material proportions for the soil-cement-bentonite mixture. The mix design utilized site soils, American River water, bentonite and cement. The objective of the initial mix design concentrated on the following areas:

a) Characterize the proposed materials.
b) Test and develop a workable soil-cement-bentonite mixture with a maximum allowable hydraulic conductivity of $5 \times 10^{-7}$ cm/sec and a minimum unconfined compressive strength of 15 psi at 28 days.
c) Formulate and test soil-cement-bentonite backfill mixture
Based on the results of the initial pre-construction testing (Tier 1), a second tier of testing was implemented during initial start-up activities. Due to the short construction schedule (70 days), the additional objective of the second tier of testing was to meet the specified 28-day hydraulic conductivity requirement in seven days.

3.3 Materials

The following materials were utilized during mix design preparation:

Water

Local tap water was used for bentonite slurry mixing. American River water was used to permeate the samples. Tap water was tested to verify compliance with the following standards:

a) A pH equal to 7.0 plus or minus 1.0.
b) Total dissolved solids not greater than 500 parts per million.
c) Oil, organics, acids, alkali, or other deleterious substances not greater than 50 parts per million each.
d) Hardness less than or equal to 50 ppm.

Bentonite

Sodium cation base montmorillonite powder (premium grade Wyoming - type bentonite) was used for bentonite slurry mixing. The bentonite conforms to the standards set forth in API Specification 13.A, Section 4.

Cement

Type II cement that conforms to ASTM C150 was used for soil-cement-bentonite mixing.

3.4 Soil Samples Collection and Testing

Soils samples were collected from eight locations approximately 1000 feet apart along the proposed slurry wall alignment. The samples included drill cuttings and soils collected at five-foot intervals using the split spoon method.

The samples were tested for gradation, plasticity and water content. Test results confirmed the findings of the geotechnical investigation described in the existing soil conditions section. Two soil composites were prepared from different locations by blending soils from all depth intervals. The amount of fines passing the No. 200 sieve in each of the two composites were 41% and 49%.

3.5 Mix Preparation

During the pre-construction testing (Tier 1), eight mixes were prepared as shown in Table 1. The bentonite slurry contained 5.4% bentonite by weight of water, and the cement slurry contained 150% cement by weight of water. Bentonite and cement slurries were added to soil in accordance with the materials proportions indicated in Table 1. Following achieving a homogeneous soil-cement-bentonite mixture with a slump of approximately 6", the mixtures were placed in 2" x 4" plastic cylinders for hydraulic conductivity and unconfined compressive strength testing. The cylinders were cured for a period of seven days at room temperature.
prior to testing. The cylinders were capped to prevent drying during curing. The samples were tested for hydraulic conductivity at 7, 14, and 28 day intervals in accordance with ASTM D5084 with the following parameters:

- **Average effective confining stress:** 10 psi
- **Hydraulic gradient:** 5
- **Permeate:** American River water adjacent to the Construction site.
- **Back pressure:** Sufficient to ensure skempton's pore pressure "B" parameter greater than or equal to 0.95.

The samples were tested for unconfined compressive strength at 7, 14, and 28 days in accordance with ASTM C39.

In order to meet these objectives, additional testing was required to achieve a maximum permeability of $5.0 \times 10^{-7}$ cm/sec at 7 days. This was due to the short construction schedule that did not allow any float time for remedial work should any of the samples do not meet the target results at 28 days. In addition, in order to minimize the overall water to solids ratio of the backfill and thus improve its permeability and strength characteristics, the bentonite slurry was mixed in a concentrated form at the rate of 11% by weight of water (higher solids content). The second tier testing produced a permeability of $4.7 \times 10^{-7}$ cm/sec and an unconfined comprehensive strength of 11 psi at 7 days. These results are attributed to decreasing the water content in the backfill.

<table>
<thead>
<tr>
<th>MIX NUMBER</th>
<th>GRAIN SIZE (% PASSING)</th>
<th>% BENTONITE ADDED BY WEIGHT OF SOIL</th>
<th>% CEMENT ADDED BY WEIGHT OF SOIL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#4</td>
<td>#30</td>
<td>#200</td>
</tr>
<tr>
<td>1B</td>
<td>100</td>
<td>94</td>
<td>49</td>
</tr>
<tr>
<td>2B</td>
<td>100</td>
<td>94</td>
<td>49</td>
</tr>
<tr>
<td>3B</td>
<td>100</td>
<td>94</td>
<td>49</td>
</tr>
<tr>
<td>4B</td>
<td>100</td>
<td>94</td>
<td>49</td>
</tr>
<tr>
<td>5B</td>
<td>100</td>
<td>94</td>
<td>49</td>
</tr>
<tr>
<td>6B</td>
<td>100</td>
<td>94</td>
<td>49</td>
</tr>
<tr>
<td>7B</td>
<td>100</td>
<td>94</td>
<td>41</td>
</tr>
<tr>
<td>8B</td>
<td>100</td>
<td>94</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 1 Mix Proportions

### 3.6 Test Results and Mix Selection

The hydraulic conductivity and unconfined compressive strength results are shown in Table 2. Mix no. 5B was selected, which produced the maximum hydraulic conductivity of $5 \times 10^{-7}$ cm/sec and minimum unconfined compressive strength of 15 psi at 28 days. However, this mix was modified during the second tier testing to utilize a high concentration bentonite slurry (11% by weight of water) in lieu of the 5.4% bentonite slurry used initially. This modified mix produced a permeability of $4.7 \times 10^{-7}$ cm/sec. and an unconfined compressive strength of 11 psi at 7 days.
### Table 2 Permeability and Unconfined Compressive Strength Results

<table>
<thead>
<tr>
<th>MIX NO.</th>
<th>W/C %</th>
<th>Permeability @ 7 days (cm/sec)</th>
<th>Permeability @ 14 Days (cm/sec)</th>
<th>Permeability @ 28 Days (cm/sec)</th>
<th>Strength psi @ 7 days</th>
<th>Strength psi @ 14 days</th>
<th>Strength psi @ 28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>67.9</td>
<td>$8.0 \times 10^{-7}$</td>
<td>$8.7 \times 10^{-7}$</td>
<td>$7.8 \times 10^{-7}$</td>
<td>10</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>2B</td>
<td>57.1</td>
<td>$5.9 \times 10^{-7}$</td>
<td>$6.8 \times 10^{-7}$</td>
<td>$4.4 \times 10^{-7}$</td>
<td>13</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>3B</td>
<td>68.1</td>
<td>$5.5 \times 10^{-7}$</td>
<td>$6.5 \times 10^{-7}$</td>
<td>$5.1 \times 10^{-7}$</td>
<td>9</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>4B</td>
<td>69.4</td>
<td>$5.4 \times 10^{-7}$</td>
<td>$7.0 \times 10^{-7}$</td>
<td>$5.6 \times 10^{-7}$</td>
<td>8</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>5B</td>
<td>57.8</td>
<td>$4.6 \times 10^{-7}$</td>
<td>$5.6 \times 10^{-7}$</td>
<td>$4.3 \times 10^{-7}$</td>
<td>10</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>6B</td>
<td>46.7</td>
<td>$5.0 \times 10^{-7}$</td>
<td>$5.5 \times 10^{-7}$</td>
<td>$4.2 \times 10^{-7}$</td>
<td>11</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>7B</td>
<td>52.7</td>
<td>$7.1 \times 10^{-7}$</td>
<td>$5.1 \times 10^{-7}$</td>
<td>$4.2 \times 10^{-7}$</td>
<td>18</td>
<td>23</td>
<td>28</td>
</tr>
<tr>
<td>8B</td>
<td>47.5</td>
<td>$4.7 \times 10^{-7}$</td>
<td>$2.6 \times 10^{-7}$</td>
<td>$1.8 \times 10^{-7}$</td>
<td>25</td>
<td>32</td>
<td>42</td>
</tr>
</tbody>
</table>

### 3.7 Site Preparation

The slurry wall was excavated with large hydraulic excavators with a width of 14 feet. The levee crown is 21 feet wide, which was not sufficient access for the large excavators or other heavy equipment. A work pad was constructed by excavating 2 feet of the existing levee crown, and placing the excavated soils on the waterside slope of the levee. The levee crown was excavated four feet at the two locations under the overhead power lines to provide additional clearance from the power lines. The construction work pad at the levee crown with a width of 30 feet provided access to the trench for heavy equipment. Also, the site preparation work included constructing temporary ramps for access and backfill preparation ponds. A view of the construction work pad and backfill mixing ponds is shown in Figure 4.

![Figure 4](image)

**Figure 4**
Work Pad and Backfill Mixing Ponds

### 3.8 Bentonite Slurry Mixing for Trench Excavation

The bentonite slurry (5-6% bentonite by weight of water) was produced at a batch plant using a jet shear mixer. This mixer has the capability to produce up to 500 gallons of hydrated bentonite slurry per minute. The plant was powered by an electric generator. Mixing was achieved by adding bentonite powder from a 4000 lb. bag while continuously mixing the water through a low volume high-pressure nozzle. The bentonite slurry was transferred from the jet shear mixer into an adjacent slurry pond where slurry was circulated and hydrated prior to...
introduction into the trench. Two (2) 6-inch trash pumps were used to circulate and agitate slurry in the pond.

3.9 High Concentration Bentonite Slurry Mixing for Backfill Preparation

The high concentration bentonite slurry (10 - 12% bentonite by weight of water) was produced in a 10,000-gallon batch plant with a high speed colloidal mixer. This mixer has the capability to produce up to 5000 gallons of high concentration bentonite slurry per hour. The mixer used a multiple blade vertical mixing arm inside a baffled tank in combination with a 6-inch trash pump to mix and re-circulate the slurry. The mixer was powered by an electric generator. Colloidal mixing was achieved by adding bentonite powder while continuously mixing the water with two layers of mixing blades, and re-circulating with a six-inch trash pump. Admixtures such as thinners (Lignosulfonate) and soda ash were added during the mixing process to allow for the production of the high concentration bentonite slurry. The mixing blades sheared the slurry against vanes positioned inside the mix tank. Shearing action was created by the mixing blades, vanes in the mixer, and the pump impeller. Mixing was continued until the bentonite appeared homogeneous. The high concentration bentonite slurry was transferred from the mixer into an adjacent backfill mixing pond where it was mixed with soils and cement slurry to produce the soil-cement-bentonite backfill mixture.

3.10 Cement Slurry Mixing

The cement slurry was produced at a batch plant in a 5 cy high colloidal mixer. This mixer has the capability to produce up to 500 gallons of cement slurry every ten minutes. The mixer was powered by an electric generator. Mixing was achieved by adding cement at the rate of 150% by weight of water from an adjacent silo while continuously mixing the water with two layers of mixing blades, and re-circulating with a six-inch trash pump. Mixing of cement slurry continued until the cement slurry appeared homogeneous and the minimum unit weight was achieved. The cement slurry was transferred from the colloidal mixer into an adjacent backfill mixing pond where it was mixed with high concentration bentonite slurry and soils to produce the soil-cement-bentonite mixture.

3.11 Slurry Wall Excavation

The slurry wall was excavated through the working pad to the design depth of 70 feet. At some locations where the gravel and cobble layer extended to a depth of 70 feet or greater, the slurry wall was excavated deeper than 70 feet to allow removal of the gravel and cobbles. Excavation was completed with four (4) excavators, equipped with long sticks, which were capable of excavating to a depth of 80 feet (See Figure 5). The bentonite slurry level was maintained in the trench between 6 inches and 18 inches of the working pad elevation. Excavation was completed into the ML or the SC materials to a minimum depth of 70 feet. Excavated soils were placed in articulated dump trucks and transported to the mixing area. Excavated soils that contained cobbles and gravel were stockpiled for off site disposal. Suitable soils were blended and homogenized at a prepared backfill mixing pond in accordance with the procedures used during the laboratory mix design.
3.12 **Soil-Cement-Bentonite Backfill Preparation and Placement**

Soil-Cement-Bentonite backfill (backfill) was mixed in a prepared earthen pond (backfill mixing pond) using a hydraulic excavator. A known volume and density of homogenized excavated soils was mixed with a known volume and density of high concentration bentonite slurry and cement slurry in accordance with the laboratory mix design proportions. The amount of slurries added was measured with flowmeters. The backfill materials were mixed thoroughly into a relatively homogeneous mass free from lumps of unmixed soil.

The backfill was transported from the mixing pond using trucks to the open trench where it was placed using a small excavator. Backfill was initially placed using a ramp excavated in the soil on one end of the trench. The ramp or lead-in trench permitted a smooth easing of the backfill into place without the potential for segregation of the backfill or the accidental entrapment of slurry. A lead-in trench was not possible at the Howe Avenue and Watt Avenue ends of the slurry wall due to access restrictions. A concrete pump was utilized to tremie the backfill at these locations until the lead-in trench was established. Placement continued from one end of the trench to the other by always placing new backfill on the leading face of previously placed backfill. In this manner, the backfill displaces the slurry, creating a continuous barrier of soil-cement-bentonite backfill without voids or entrapped slurry. Backfill in the trench formed a relatively flat slope of approximately 5:1 to 8:1. The toe of backfill slope was kept a minimum distance of 50 feet from the toe of excavation to maximize the stability of the trench.

3.13 **Impervious Cap Construction and Site Restoration**

Following construction of the soil-cement-bentonite slurry wall, a cap consisting of compacted impervious fill materials was placed between the top of the slurry wall and the final grade of the levee. The excavated soils that were placed on the land side slope of the levee to provide a wide work pad did not meet the plasticity requirements for the impervious fill materials, and were removed off the site. Following restoration of the original levee crown and cap construction, asphalt concrete pavement over an aggregate base was placed along the levee crown. Site restoration included removal and grading of staging areas and mixing...
ponds, transportation and off site disposal of excess excavated soils including cobbles and gravel and hydro-seeding of disturbed areas.

4.0 Quality Control

The project specifications required a very thorough quality program. This program included slurry and backfill testing, and procedures to check depth, excavated materials, slurry wall alignment and materials proportions. Test results, abnormalities, excavation, and backfill profiles and sampling procedures were recorded on the daily quality control reports. The following describes the quality control testing and procedures:

4.1 **Bentonite Slurry for Trench Excavation**

Bentonite slurry used for trench excavation was tested in accordance with the parameters shown in Table 3. Test results were recorded on the daily quality control report.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>STANDARD</th>
<th>TYPE OF TEST</th>
<th>MINIMUM FREQUENCY</th>
<th>SPECIFIED VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite</td>
<td>API Specification 13A</td>
<td>Certificate of compliance</td>
<td>1 per truck load</td>
<td>Premium grade sodium cation montmorillonite</td>
</tr>
<tr>
<td>Bentonite Slurry at the mixer</td>
<td>API Specification 13B-1</td>
<td>Viscosity filtration density</td>
<td>2 per shift, 2 per shift</td>
<td>40 seconds minimum, 20 c.c in 30 minutes at 100 psi ≥ 6.4 lb/cf</td>
</tr>
<tr>
<td>Bentonite Slurry in the trench</td>
<td>API Specification 13B-1</td>
<td>Viscosity filtration density</td>
<td>2 per shift, 2 per shift</td>
<td>40 seconds minimum, 30 c.c in 30 minutes at 100 psi Between 64 and 85 lb/cf</td>
</tr>
</tbody>
</table>

Table 3 Bentonite Slurry Properties

4.2 **High Concentration Bentonite Slurry for Backfill Preparation**

This slurry was required for backfill preparation, and was not introduced in the trench to maintain its stability. Continuous inspection of the slurry was required to insure that it was free of unmixed lumps of bentonite. Bentonite was added from 4,000-pound bags. The amount of water required for each batch was measured using a flowmeter.

4.3 **Cement Slurry**

The amount of water required for each batch was measured using a flowmeter. Cement was added in bulk from an adjacent silo at the rate of 150% by weight of water. Quality control of cement addition was maintained by measuring the density of the cement slurry prior to introduction into the backfill mixing pond.

4.4 **Depth and Trench Alignment**

The depth of the slurry wall was measured and recorded every ten (10) feet along the cutoff wall centerline. The depth profile of the open trench and the backfill slopes were recorded and plotted daily. This allowed for verification of trench stability and backfill placement. The trench alignment and offset control points were surveyed prior to construction.
activities. Survey markers with station locations were placed at ten (10) feet intervals along the cutoff wall centerline.

4.5 Excavated Soils
Excavated soils were inspected by a civil engineer to verify that they were consistent with the soils encountered during site investigation and mix design preparation. In some locations, excavation was extended beyond the design depth of seventy (70) feet due to the presence of gravel and cobbles at that depth. Description and classification of trench materials were completed in accordance with ASTM D 2488. Soil classifications were recorded on the daily quality control report.

4.6 Soil-Cement-Bentonite Backfill
The volume of soil used in each backfill preparation batch was measured by counting the number of excavator buckets added into the backfill pond. The amounts of cement slurry and bentonite slurry were measured using a flowmeter. Two soil-cement-bentonite samples were collected every shift. The samples were stored at the site in an undisturbed location for a period of five days prior to transportation to the independent laboratory for testing. The number of backfill batches, slump test results, and backfill density results were recorded on the daily quality control report.

4.7 Laboratory Quality Control Testing
An independent testing laboratory conducted permeability and unconfined compressive strength testing of 96 soil-cement-bentonite samples at 7, 14 and 28 days. Two soil-cement-bentonite samples were collected each shift from the backfill preparation pond prior to placement into the trench. The test results plotted in Figures 6, 7, 8 and 9 were consistent with the mix design results and exceeded the maximum permeability criteria of $5 \times 10^{-7}$ cm/sec and the minimum unconfined compressive strength of 15 psi at 28 days.
5.0 Conclusion/Recommendations

The project was completed by constructing 540,000 square feet of soil-cement-bentonite slurry wall to a depth of seventy feet during a nine-week period. To facilitate future projects, we recommend the following:

1) Characterize completely and accurately the subsurface soils and required depth of excavation. Subsurface investigations are required at 100-500 feet intervals along the centerline of the proposed slurry wall.

2) Allow a minimum two months to conduct a thorough mix design utilizing proposed construction materials. The mix design simulates field conditions and provides quality control parameters.

3) Provide sufficient staging areas to stockpile excess excavated soils, store materials, and construct adequate mixing ponds.

4) Achieve the permeability requirement at seven (7) or fourteen (14) days instead of twenty-eight (28) days. Re-excavation due to failed samples is costly, and may require re-mobilization of equipment and access to restricted areas.

5) Provide experienced personnel in soil-cement-bentonite slurry wall construction. Personnel who are familiar with soil-bentonite slurry wall may not be familiar with the complex construction methods and testing of soil-cement-bentonite slurry walls.

6) Proper handling of soil-cement-bentonite samples. These samples which contain low strength materials require storage at an undisturbed location for a minimum period of five (5) days prior to transportation to the laboratory to avoid fracture or damage.

References:

