Soil-Cement Walls for Excavation Support

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Abstract: The Cement Deep Soil Mixing (CDSM) method introduces and mixes cementitious materials with in situ soils using hollow-stem rotating shafts equipped with a cutting tool at the tip and mixing paddles above the tip. CDSM generally produces a soil-cement panel consisting of three overlapping soil-cement columns. The soil-cement panel is then extended to form walls, which are effective for excavation support and groundwater control due to the continuity and low permeability of soil-cement walls. Two design approaches could be taken in the application of CDSM for excavation support: 1) single wall design and 2) gravity wall design. The former one is treated as a wall technology and the latter one is treated as a soil stabilization method. This paper will review the CDSM equipment and installation procedures for the construction of these two types of soil-cement walls. Four case examples are used to illustrate the design and application of these two types of soil-cement walls.

I INTRODUCTION

This paper presents the application of soil-cement walls for excavation support using two categories of in situ soil mixing methods, one for single row wall installation and the other for ground stabilization. The term "CDSM" (Cement Deep Soil Mixing) was initiated by Port of Oakland together with its consultants to represent the in situ soil mixing procedures it selected to use for the construction of soil-cement walls, buttresses, and blocks for the development or expansion of its facilities at the Port of Oakland and the Oakland International Airport. This term is adopted in this paper as a generic term to represent the soil mixing methods used in the four project examples without differentiating their origins, unique equipment designs and procedures, and special areas of applications. The soil mixing equipment and procedures used for these four projects can be traced back to their origins in Japan. However, they are used in the United States in more liberal and innovative manners to achieve performance requirements for specific applications in each project. The first part of this paper is a review and discussion of the two soil-mixing methods, wall methods and soil stabilization methods. This is followed by the presentation of four case examples for the application of earth retention: 1) CalPERS Headquarters Expansion Project, Sacramento, California; 2) Skyport Drive Grade Separation Project, San Jose, California; 3) Oakland Airport Roadway Project, Oakland, California; and 4) Delayed Coker Unit Project, St. Croix, US Virgin Islands. The first two projects used single wall design and the latter two projects used gravity wall design.

II SOIL MIXING METHODS FOR WALL INSTALLATION AND SOIL STABILIZATION

Based on the concept of mixed-in-place piles initiated in the 1950's in the United States, Japanese constructors in the late 1960's and early 1970's installed single mixed-in-place soil-cement piles along a row to create a wall for excavation support and groundwater control needed for the construction of basements or other subsurface structures. Due to the high groundwater conditions in most of the major cities in Japan, wall continuity and uniformity became the major requirements of soil-cement walls for reliable groundwater control to avoid settlement or failure of buildings or other facilities adjacent to excavations. To overcome the deficiency of a single-auger soil-mixing tool, Seiko Kogyo developed the Soil Mix Wall (SMW) method, which uses a triple-axis auger and staggered installation placement to produce a single-row soil-cement wall with reliable material uniformity and wall continuity. This method is recognized as a wall installation technology in Japan. Due to the need to install steel reinforcement into the single-row soil-cement wall for resisting lateral forces, high water cement ratio grout with bentonite is

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used to produce lower strength soil-cement with high fluidity to facilitate the installation of steel H-piles or sheet piles. Since its full-scale application in 1976, more than 5,000 SMW walls have been installed. Attempts were made to use the SMW method for large-scale-area ground stabilization; however, this extended application was not widely accepted in Japan due to its origin and classification as a wall method. This method was introduced to the United States in 1987 for the construction of a seepage cutoff wall and soil-cement cells for foundation stabilization under the Jackson Lake Dam in Wyoming. The first application of SMW wall as an excavation support wall in the United States was in 1990 for the construction of a Wet Weather Storage Basin for East Bay Municipal Utility District in Oakland, California. The CDSM method used for the first two project examples of this paper is a wall method with improved controls over mixing energy and grout distribution for uniformity of soil-cement produced.

There are numerous varieties of soil mixing methods developed in Japan for the treatment of soft ground. The variations mainly include design of the mixing tool; application of soil mixing energy mechanically, hydraulically, or a combination of both; and addition of hardening agents in wet or dry form. Recently, a general term "Deep Mixing Method" (DMM) was accepted to cover these soil-mixing methods developed worldwide. Most of the Japanese wet DMM methods are based on the results of initial research and development performed in late 1960's to early 1970's by the Port and Airport Research Institute (PARI) of the Japanese Ministry of Transportation in conjunction with several general contractors. The research and development of PARI aimed at the treatment of soft marine deposits under or adjacent to the harbor to produce massive soil-cement configurations for use as foundations or for maintaining the stability of the port structures such as sea walls, breakwater, quay and other port facilities. In contrast to the wall method, multiple rows of soil-cement panels or walls are installed to form a block or monolith of soil-cement underground to serve the design functions. While the material design of soil-cement remains unchanged, the geometric design continues to evolve for more efficient use of the soil-cement structures. The combination of walls or panels to form a soil-cement grid structure reduces the percentage of soil treatment, however, it serves the equivalent functions of a soil-cement block for bearing capacity, settlement control, stability or liquefaction prevention. The soil mixing method used for the latter two project examples of this paper is a soil stabilization method with modifications on the design of the mixing tool and mixing procedures to meet the project demands in the United States.

III REINFORCEED SOIL-CEMENT WALLS FOR EXCAVATION SUPPORT

A. CalPERS Headquarters Expansion Project, Sacramento, California

1. Proposed Construction

This project included construction of a four- and six-story building with two levels of below-grade parking. An excavation to a depth of 32 feet below existing ground surface was needed for the construction of the below-grade parking structure. A soil-cement wall along the perimeter of the building was constructed for use as seepage control and excavation support during the construction of the below-grade parking structure. A site plan with the alignment of the soil-cement wall is shown in Figure 1.

2. Subsurface Conditions

The site is underlain by 6 to 14 feet of silty sand fill and soils disturbed by past developments. The fill is underlain by clayey to sandy silts to depths of 25 to 35 feet below the existing grade.

The silts are underlain by clean sands with occasional layers of silty sands to depths of about 60 to 65 feet (Wallace-Kuhl Report, 2001). The top of this stratum was exposed at the bottom of the basement excavation. A dense stratum of sandy gravels and large cobbles underlies the sands and extends to depths of 100 to 120 feet. This stratum is very permeable and imposes a major dewatering challenge to the construction of the below-grade parking structure. The gravel and cobble stratum is underlain by partially cemented clayey silts, part of the Riverbank Formation, to the maximum exploration depth of 145 feet. A representative boring log is shown in Figure 2. The groundwater table ranges from 7 feet to 15 feet below grade depending on the season.

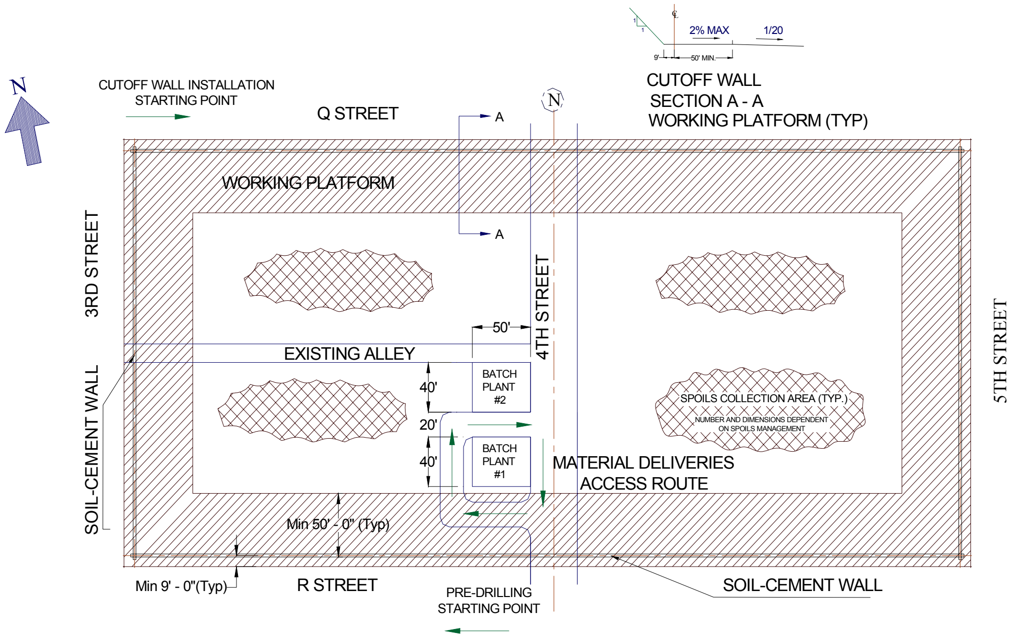

Figure 1: Site Plan

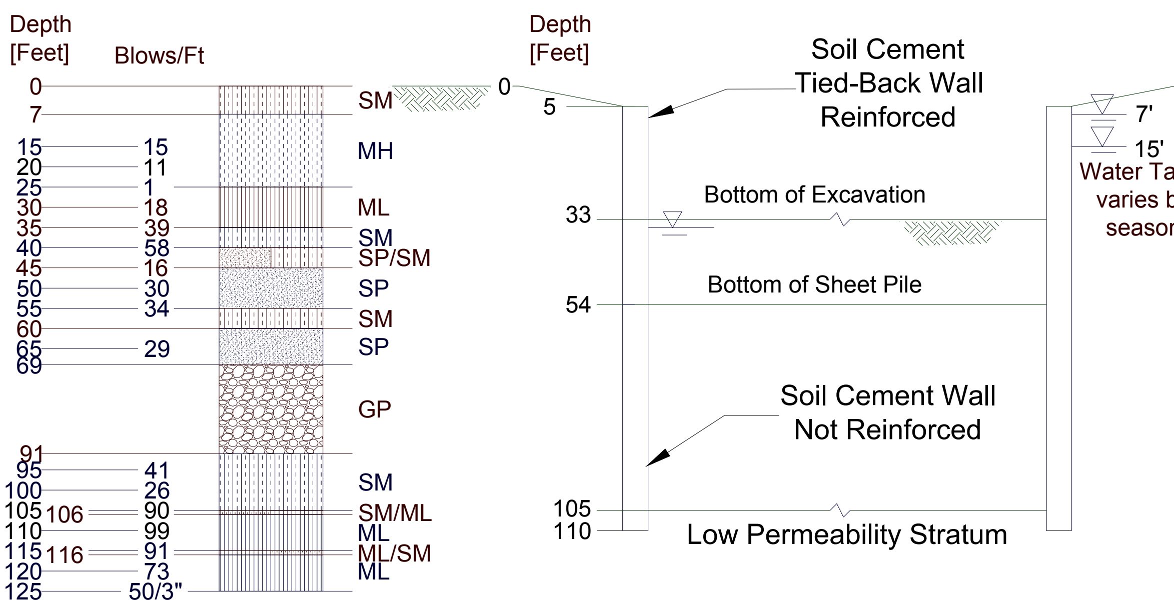

Figure 2: Representative Boring Log and Cross Section

3. Design of Seepage Cutoff / Excavation Support Wall

The seepage cutoff / excavation support wall was designed by Mueser Rutledge Consulting Engineers. As discussed in the letter report of Mueser Rutledge Consulting Engineers (2001), the site is underlain by a major aquifer, consisting of very permeable sands, gravels and cobbles. The aquifer is recharged by the Sacramento River, resulting in seasonal fluctuation in groundwater levels with river stages. This dynamic aquifer must be dewatered or otherwise controlled to permit construction of the underground parking. A perimeter cutoff wall was designed to extend to the low permeable Riverbank Formation to isolate the deep excavation from the fluctuation of the groundwater levels and simplify the basement construction. A maximum permeability of 1×10^{-6} cm/sec was specified for the cutoff wall. The Riverbank Formation was expected to perform at an average permeability of 2.3×10^{-6} cm/sec based on the laboratory testing of samples recovered. Assuming an average permeability of 1×10^{-6} cm/sec for the 30-inch thick cutoff wall, and a permeability of 2×10^{-6} cm/sec for a 5- foot thick Riverbank Formation as a closure layer, Mueser Rutledge estimated a steady state seepage through the cutoff wall and the closure formation to be 65 gal/min during the maximum expected draw down from an elevation of +5 (13 feet deep) outboard to an elevation of –17 (35 feet deep) inboard of the cutoff wall. Approximately half of this flow is upwards through the Riverbank Formation. The contract specifications allow for seepage quantity up to 200 gal/min.

Steel sheet piles were designed to reinforce the upper portion of the cutoff wall to support the lateral earth pressure and the 600-psf surcharge outside the wall and a groundwater table at an elevation of +10 feet (8 feet deep) outboard. The sheeting relies on two tieback levels and undisturbed soil below subgrade for support. Depth of embedment was approximately 15 feet below the bottom of the excavation, leaving the lower 60- to 70-foot portion of un-reinforced wall to serve as the sole seepage barrier as shown in Figure 2. Sheeting movements on the order of two inches were anticipated.

4. Wall Installation

A single row soil-cement wall was produced along the perimeter of the area to be excavated using the CDSM method. A triple axis auger (mixing tool) with discontinuous auger flights and mixing blades was used to mix the in situ soils with cement grout to form a soil-cement panel. The panels were then extended to form a continuous wall as shown in Figure 3a. Based on additional borings made along the perimeter of the excavation, the soil-cement cutoff wall was extended to a depth varying from 110 to 128 feet, with about a 10-foot key into the Riverbank Formation. The 10-foot key into the Riverbank Formation was constructed to cut off any sand lenses in the upper portion of the Riverbank Formation. Sheet piles as shown in Figure 3b were inserted into the soil-cement wall before the hardening of the soil-cement.

5. Excavation and Seepage Control

Major excavation and inboard pumping were started after the completion of the wall installation. The pumping rate exceeded 100 gal/min in the early excavation stage and gradually reduced to a range between 50 to 60 gal/min after storage was removed. The groundwater table was maintained at approximately 3 feet below the bottom of the excavation using two deep wells. Without the barrier, approximately 9,500 gal/min discharge was estimated and would require 35 deep wells to maintain the site dry for construction. A view of the wall and bottom of the excavation is shown in Figure 4.

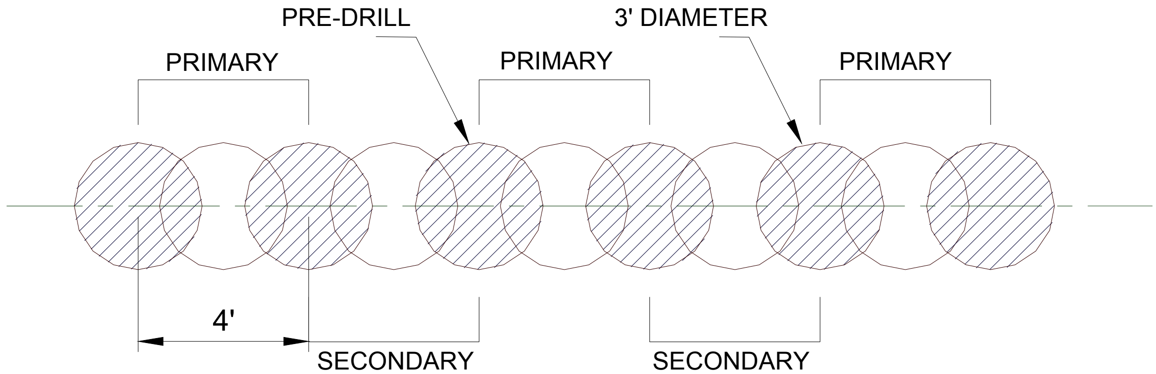

Figure 3a: Soil-Cement Cutoff Wall

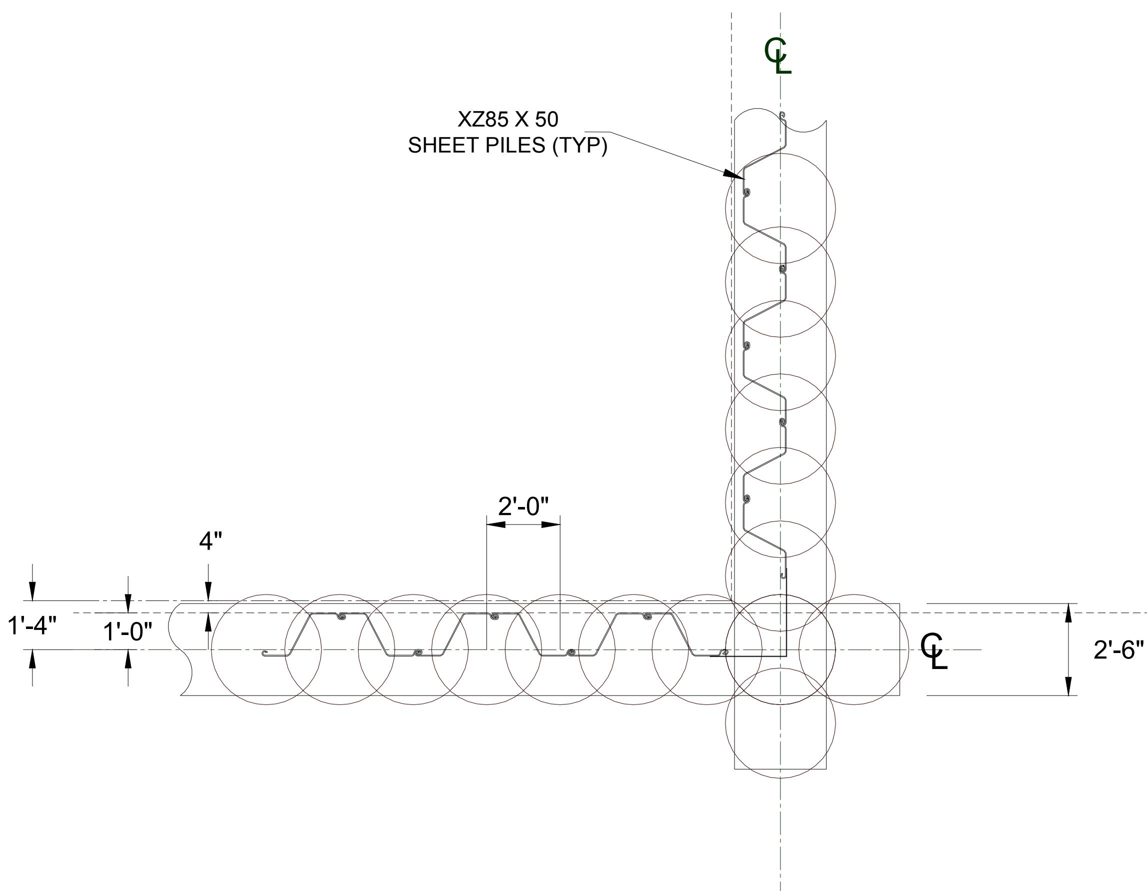

Figure 3b: Soil-Cement Excavation Support Wall

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Figure 4: Soil-cement Tied-Back Wall with Sheet Pile Excavation Support System

B. Skyport Drive Grade Separation Project, San Jose, California

1. Proposed Construction

This grade separation project consists of a cut-and-cover tunnel, a depressed road with two channel walls along Airport Boulevard and a temporary slab bridge to the south of the proposed tunnel as shown in Figure 5. The cut-and-cover tunnel is a cast-in-place reinforced box approximately 800 feet long, 50 feet wide, and extends about 22 feet below finished grade. Temporary shoring will be required along the depressed roadway for construction. The maximum excavation will be about 18 to 20 feet below the existing roadway grade. Groundwater control will be required during construction.

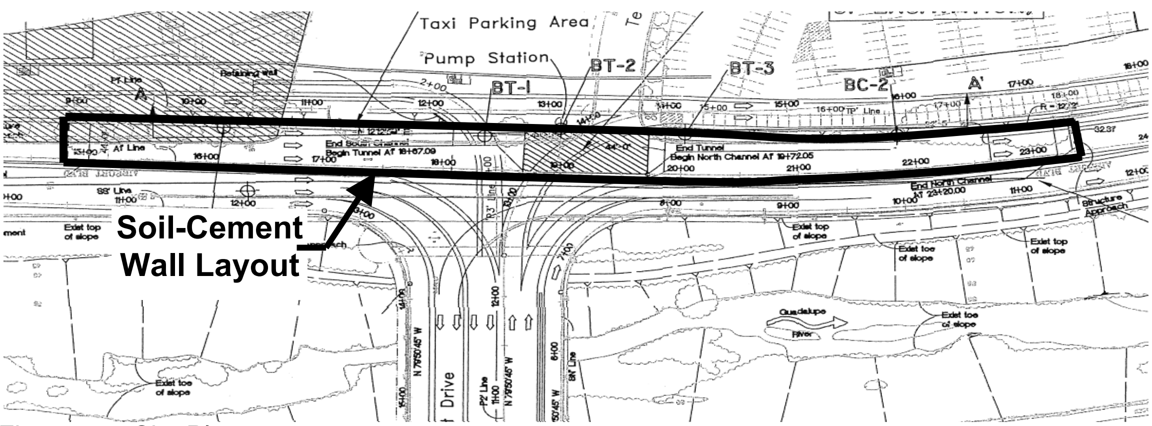

Figure 5a: Site Plan

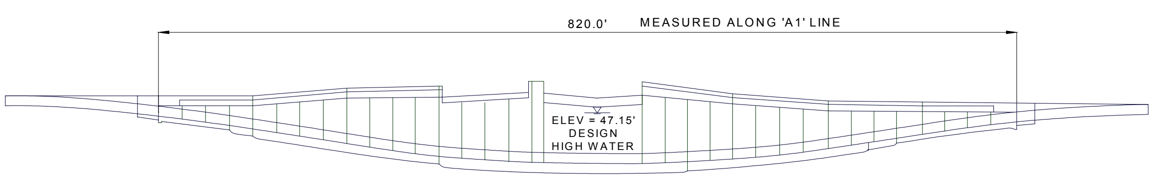

Figure 5b: Longitudinal Section

2. Subsurface Conditions

The subsurface soils along the depressed roadway generally consist of alternating clay and sand layers (Parikh Consultants Report, 2002). The clay layer extends from existing grade down to 16 feet deep on the north and to 30 feet deep on the south. The clay layer is underlain by silty to clayey sands with thickness ranging from 10 to 29 feet. Below the sand layer, the borings encountered a stiff clay layer to depths of 50 feet. A representative boring log is shown in Figure 6. The groundwater is located at approximately 15 feet below grade and is affected by water level in the Guadalupe River running within 100 to 200 feet parallel to the proposed depressed roadway. Historical records indicate that the water level could reach an elevation of 47.15 feet, which is approximately 1 foot below the existing grade of Airport Boulevard.

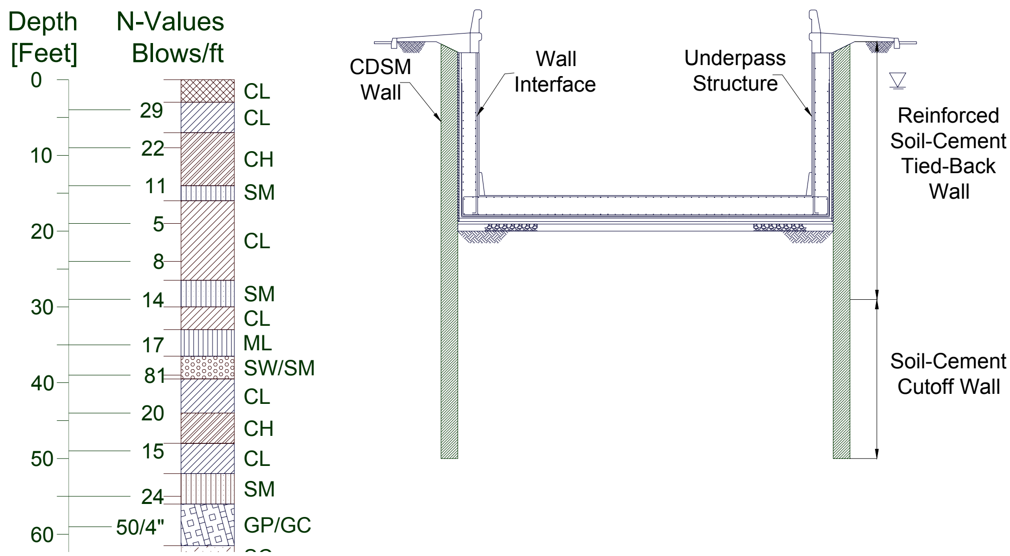

Figure 6: Representative Boring Log and Cross Section

3. Design of Seepage Cutoff / Excavation Support Wall

The construction of the depressed road and tunnel requires excavation below the groundwater table and the water level at the Guadalupe River. A soil-cement wall was recommended by Parikh Consultants, Inc. for temporary excavation support and groundwater control to maintain the groundwater below the bottom of the excavation. The cutoff portion of the soil-cement wall is designed to key into the clay layer at approximately 30 to 50 feet below the existing grade for the control of lateral flow. Due to the varying subsurface conditions, exploratory borings at 100-foot intervals were required to confirm the depths, thickness, and continuity of the clay layer for use as a closure seal below the bottom of the excavation. The lateral earth pressure and water pressure are resisted by the portion of the reinforced soil-cement wall extending only 15 feet below bottom of excavation, approximately 15 feet above the lower tip of the soil-cement cutoff wall as shown in Figure 6. H-piles (size W16x40) are used for reinforcement, which in turn are generally supported by two levels of tiebacks. In the areas where the excavation is less than 16 feet, only one level of tieback is needed. The geometric design of the soil-cement wall and steel reinforcement are shown in Figure 7. The soil-cement is required to have a maximum permeability of 1 x 10^{-6} cm/sec and a minimum 28-day unconfined compressive strength of 100 psi. Due to the high groundwater condition, the depressed road and cut-and-cover tunnel are designed as buoyancy boxes as shown in Figure 6. In addition to the use for temporary construction purposes, the soil-cement wall also provides long-term uplift resistance to the concrete structures of the depressed road and tunnel. Steel ties are welded onto the surface of the H-piles of the soil-cement wall and incorporated into the concrete walls of the depressed road and tunnel. An allowable friction resistance of 480 pounds per square foot between the surface of the soil-cement wall and native soils is used for the calculation of the uplift resistance provided by the soil-cement wall. Details of the connection are shown in Figure 7a.

4. Wall Installation

A CDSM wall will be installed using a multiple-axis auger following the layout design shown in Figure 7b. The in situ soil mixing parameters, including mixing energy and grout ratio, will be selected based on the results of laboratory trial mix study. A computer based QA/QC system will be used to monitor the wall installation on a real- time basis. H-piles will be installed immediately after the soil mixing. A total of 80,000 square feet of wall will be installed from May to July 2003.

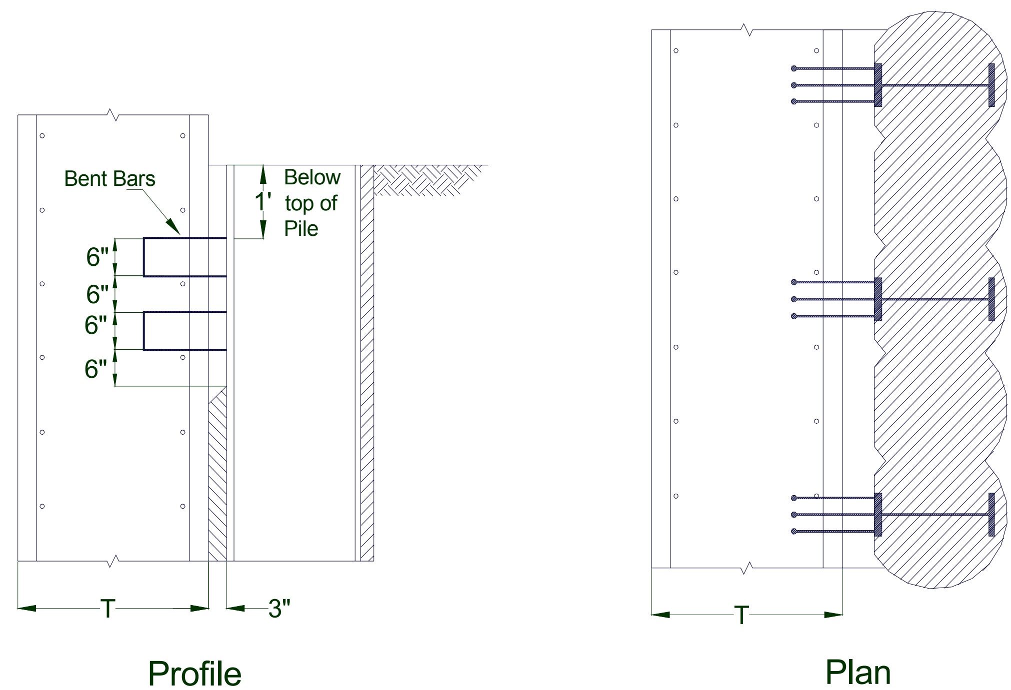

Figure 7a: Uplift Connection

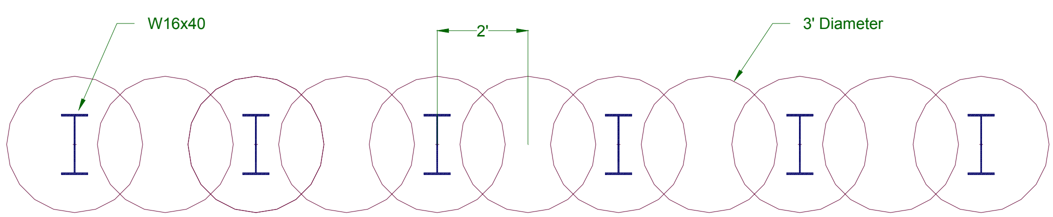

Figure 7b: Reinforcing Layout

IV GRAVITY SOIL-CEMENT WALLS FOR EXCAVATION SUPPORT

A. Oakland Airport Roadway Project, Oakland, CA

1. Proposed Construction

The Oakland airport roadway project included three new grade separation structures. The CDSM method was used to construct cutoff walls, soil-cement foundations and soil-cement gravity retaining walls for the construction of these grade separation structures. At the Air Cargo Road/Taxiway B intersection, Taxiway B will be raised a maximum of 8 feet above the existing grade, and Air Cargo road will be depressed a maximum of about 15 feet below the existing grade. This grade separation structure is located in the vicinity of a former borrow pit used to obtain sand fill during construction of the original North Field airport site in the late 1920's and 1930's. The borrow pit was abandoned in the late 1940's and was allowed to in-fill with sediments including soft silty clays, loose silts and sands. A block-type CDSM treatment was used to construct a permanent retaining structure, which also functioned as a temporary shoring system during construction. The block-type treatment also included a CDSM cutoff wall to provide permanent seepage control and reduce dewatering requirements during construction. A site plan and the layout design of the CDSM wall are shown in Figure 8a and 8b, respectively.

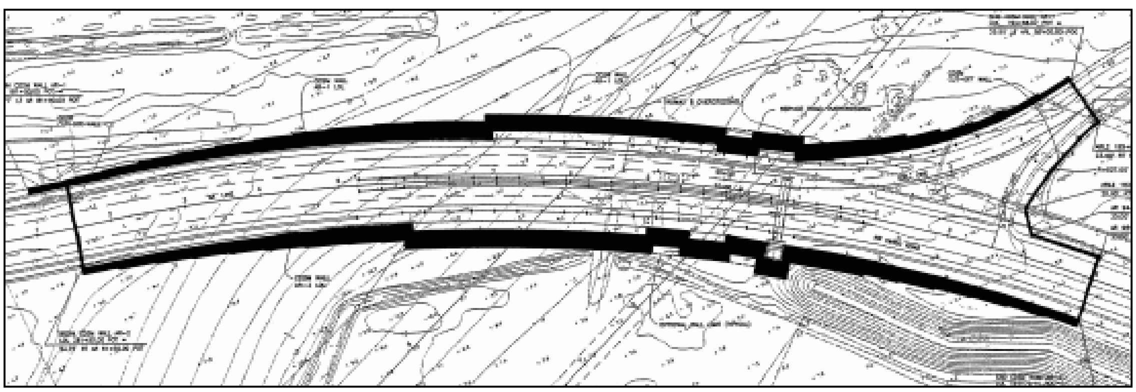

Figure 8a: Site Plan

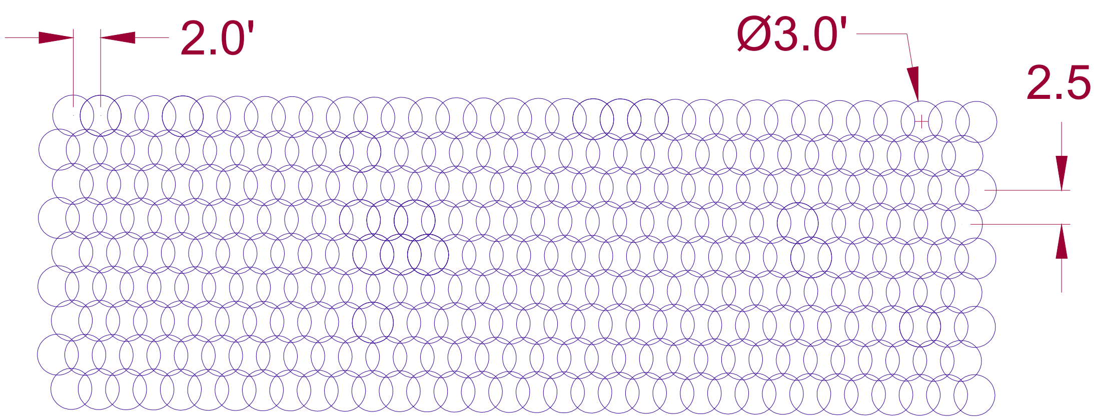

Figure 8b: Geometric Design

2. Subsurface Conditions

The subsurface soils outside the former borrow pit area generally consist of about 10 to 15 feet of sand fill overlying relatively thin deposits of soft Bay Mud, usually less than 3 feet (Geomatrix Consultants Report, 1999). The fill and Bay Mud are underlain by competent medium dense to very dense sands and medium stiff to very stiff silty or sandy clays. In areas of the former borrow pit, loose sands or silts and soft silty clay in-fill materials were encountered extending down to depths of 20 to 25 feet below the existing ground surface. An idealized soil profile along Air Cargo Road at the Taxiway B over crossing is shown in Figure 9. The sand fill and lose sand in-fill materials are subject to liquefaction during a strong earthquake. Groundwater levels at the site vary with location due to pumping activities at the airport. The groundwater levels generally vary from 5 to 10 feet below the existing ground surface.

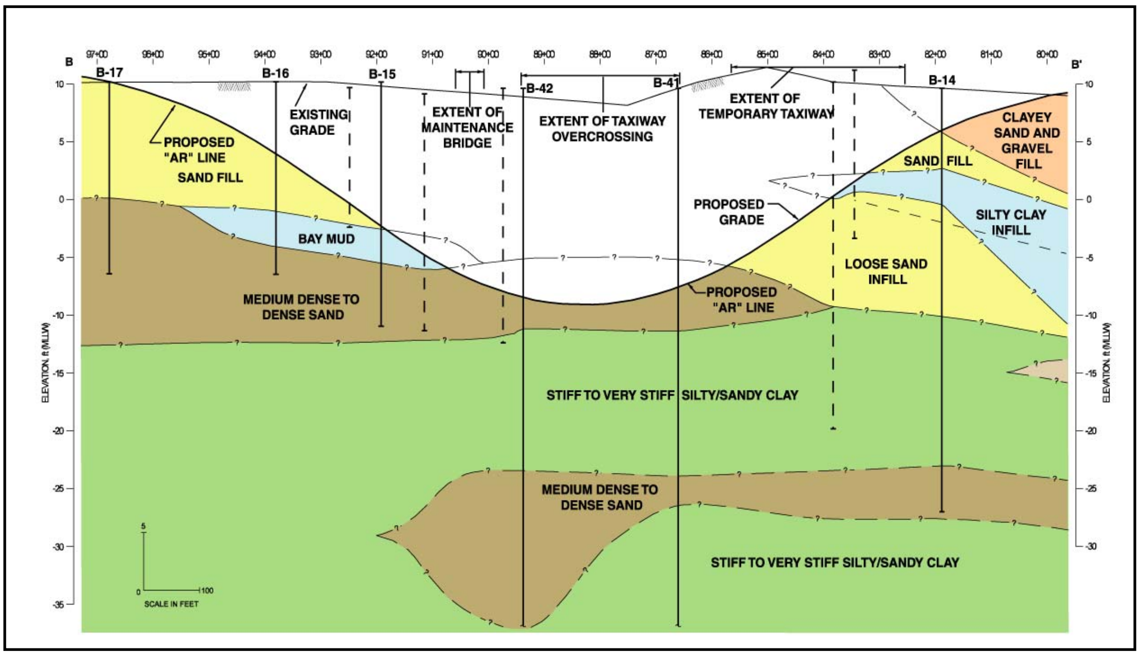

Figure 9: Idealized Soil Profile (Courtesy of Geomatrix Consultants)

3. Design of Gravity Soil-Cement Wall

A block-type treatment of CDSM columns was designed by Geomatrix Consultants, Inc. to construct permanent retaining structures along the depressed Air Cargo Road. The overlapping CDSM elements were designed as a gravity structure and included soil nails for reinforcement and a permanent concrete wall facing as shown in Figure 10. The CDSM gravity structure was designed to limit the permanent lateral deformations to approximately 6 inches during a design earthquake with a probability of exceedance of 20 percent in 50 years. Where the CDSM walls are adjacent to the abutments for the Taxiway B bridge structure, they are designed for a permanent deformation of approximately 4 inches during a design earthquake with a probability of exceedance of 5 percent in 50 years. Estimated peak ground accelerations for the two design earthquakes are 0.47g and 0.70g, respectively. The permanent deformations were estimated using pseudo-static stability methods and Newmark-type displacement analyses. Design dimensions for the CDSM gravity retaining structure are shown in Figure 10. The minimum width of the gravity wall equals the maximum excavation depth during construction and the depth of the gravity wall extended a minimum of 4 feet below the maximum depth of excavation. In areas where additional slide resistance was needed, part of the soil-cement panels were extended below the bottom of the gravity wall to act as a slide resistance key. Geocomposite drain strips behind the permanent wall facing of the gravity wall were designed to release the water pressure. Collector pipes will carry the seepage from these drain strips as well as that from the drainage layer below the Air Cargo Road pavement to a sump for pumping. To minimize the amount of water pumped from the drainage system on a permanent basis and to minimize the amount of dewatering required during construction, a CDSM cutoff wall was incorporated in the center of the soil-cement gravity wall and extended beneath the bottom of the gravity wall to reduce the flow of seepage from the gravelly soil layer under the gravity wall. The design was based on an average unconfined compressive strength of 150 psi (Yang, et al., 2001).

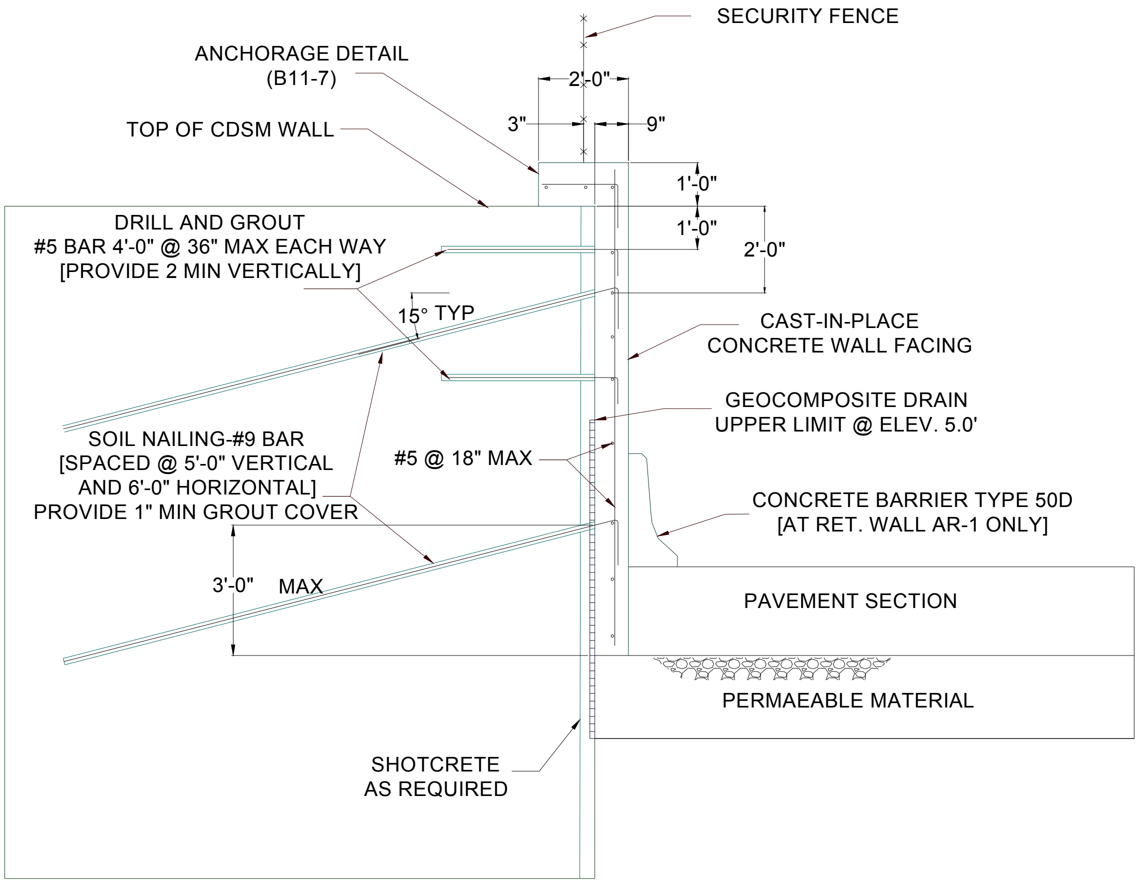

Figure 10: Design of CDSM Gravity Wall

4. Wall Installation

The installation of the CDSM gravity wall began in March 2001 and was completed in December 2001. Approximately 45,000 cubic yards of soil-cement gravity wall were installed. A view of the excavated CDSM wall is shown in Figure 11. Due to the complex subsurface conditions resulting from the historical development of the site, several test sections were performed along the alignment of the gravity wall for the confirmation or modification of the mix design and installation procedures to ensure that the design strength and uniformity could be obtained.

Figure 11a: CDSM Gravity Wall Before Installation of Facing

Figure 11b: CDSM Gravity Wall Close-up View of the Left Wall

B. <u>Delayed Coker Unit Project, St. Croix, US Virgin Islands</u>

1. Proposed Construction

The project consisted mainly of a delayed coker unit, including coker handling and storage facilities. The main delayed coker unit spreads over an area of 336 feet by 204 feet (Arango, et al., 2002). The major components of the partly underground unit are coker structures extending 330 feet high, a 26-foot deep coke pit, a 36-foot deep settling basin and a coke pad at grade. Surrounding the coke pit, pad, and settling basin is a 13-foot high concrete wall and a series of heavy concrete columns supporting a 125-foot long bridge crane. An artistic view of the finished facilities is shown in Figure 12.

2. Subsurface Conditions

The subsurface materials consist of three main strata: hydraulic fill, marine deposits, and limestone (Arango, et al., 2002). The 10 to 13 feet of fill has a 3 to 7-foot thick layer of desiccated stiff to hard silts and clays with sand, underlain by lenses of soft to medium stiff silts and clays. The hydraulic fill is underlain by the original Bay deposits, which extend down to the weathered limestone unit at depths varying from 55 to 78 feet. While variable from place to place, the marine deposits appear to consist of two continuous layers of silty to clayey sands intercalated with two layers of silty clay. The two sand layers have a standard penetration blow count, N, varying from 3 to 8 and fine contents ranging between less than 5 to 40 percent. Very low factors of safety against liquefaction, less than 0.4, were found for these two sand layers. Beneath the marine deposits is a layer of highly weathered clayey limestone, which becomes less weathered and stronger with depth. The groundwater table is encountered at 15 feet below the ground surface. A representative boring log is shown in Figure 13.

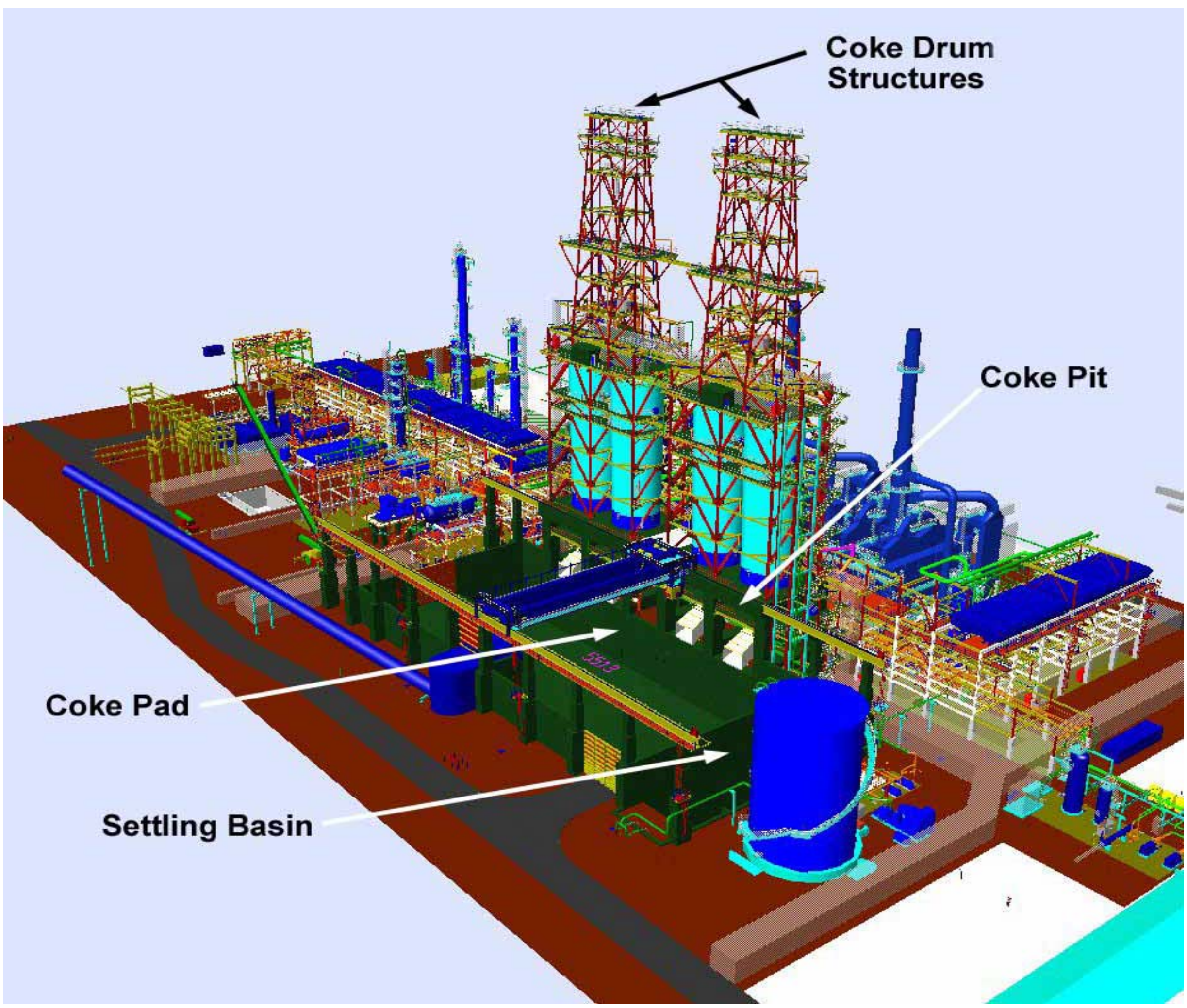

Figure 12: An Artistic View of the Finished Facilities
(Courtesy of Bechtel Corporation & Earthquake Engineering Research Institute)

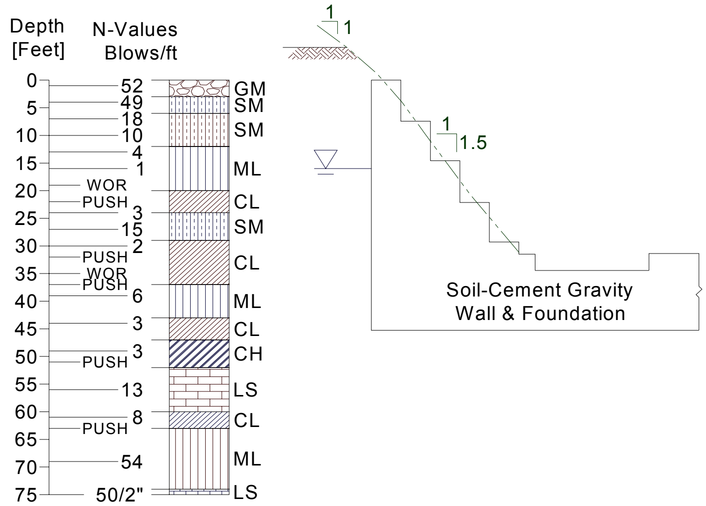

Figure 13: Representative Boring Log and Subsurface

3. Design of Soil-Cement Foundation and Gravity Wall

The soil-cement foundation and gravity retaining wall were designed by Bechtel Corporation (Arango, et al., 2002). The coker structure includes two coker drum structures, each weighing 16,500 tons, and a 403-foot high upper steel frame structure. The coker structures' massive size, weight, and mass distribution coupled with the extreme site-specific conditions of high seismic potential and hurricane force winds result in some of the most severe foundation loads in the Petroleum and Chemical Industry. A cursory assessment of the subsurface soils conditions at the site concluded that the nature and engineering properties of both the fill and marine deposits were not adequate to directly support the heavy loading imposed by the structures. Also, difficulties were anticipated in providing temporary support of excavation and control of water seepage with a 36-foot head. For the excavation, options including sloping walls, sheet piles, drilled shafts, and structural slurry walls were considered and discarded for technical/constructability reasons. In the end, a solution based on supporting excavation and structural loads on improved soil-cement utilizing the CDSM was adopted.

The CDSM solution was unique in that it provided support to the deep excavation without the use of reinforcement, sheet piling or anchors; it provided support to the heavy structural loads eliminating the need for piling; it provided stability against liquefaction; and it eliminated the need for a de-watering system for the excavation. Overlapped soil-cement columns were used to create a continuous cellular system under the structures and along the perimeter of the excavation. Soil-cement panels were extended to bear on the layer of stiff clay or weathered limestone under the site. The cells have various plan dimensions to provide different replacement ratios to satisfy different load demands as shown in Figure 14a. Areas under the coke drum structures, the retaining walls around the perimeter and the deeper settling basin required a 90 percent replacement ratio. Less severely loaded zones under the coke tank and coke pad required only 63 percent and 39 percent replacement, respectively. Details of the geometric design are shown in Figure 14b. A cross section along the deepest excavation and the forces considered in the stability analysis are shown in Figure 15. The design required for an average 90-day unconfined compressive strength of 125 psi. The required static shear strength was taken as one half of the unconfined compressive strength. The dynamic shear strength was taken as 130 percent times the value of the static strength. The elastic modulus was taken as 300 times the unconfined compressive strength.

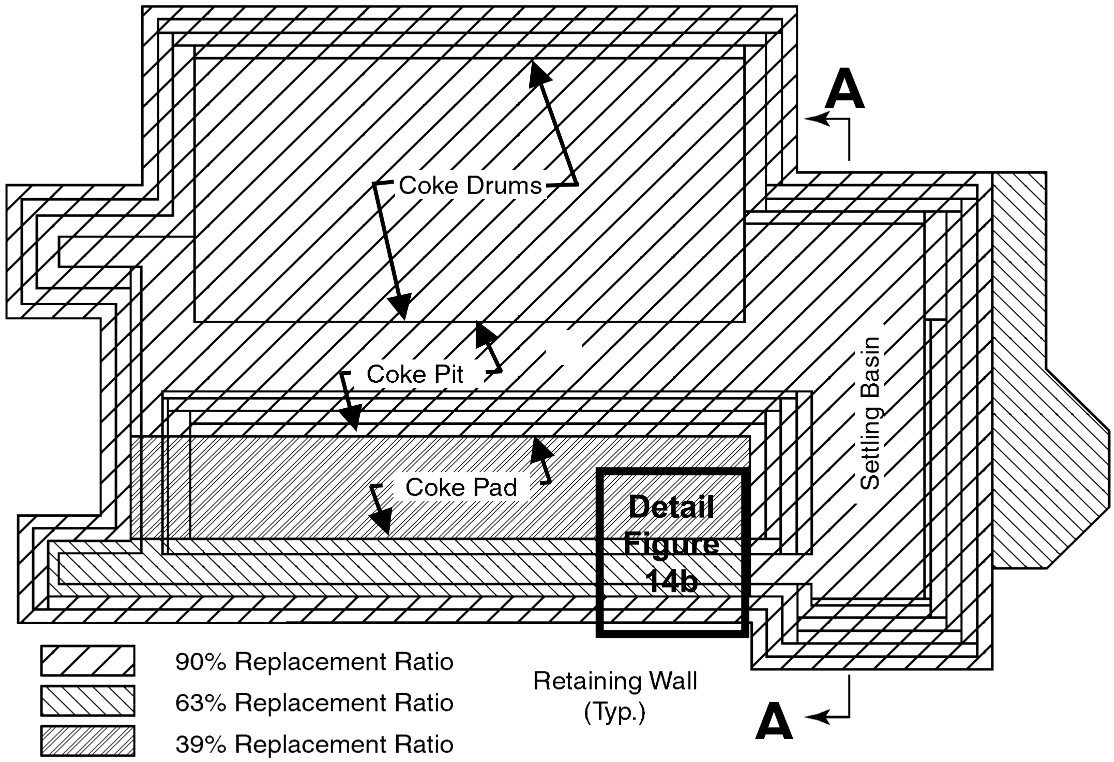

Figure 14a: Site Treatment Plan (Courtesy of Bechtel Corporation & EERI)

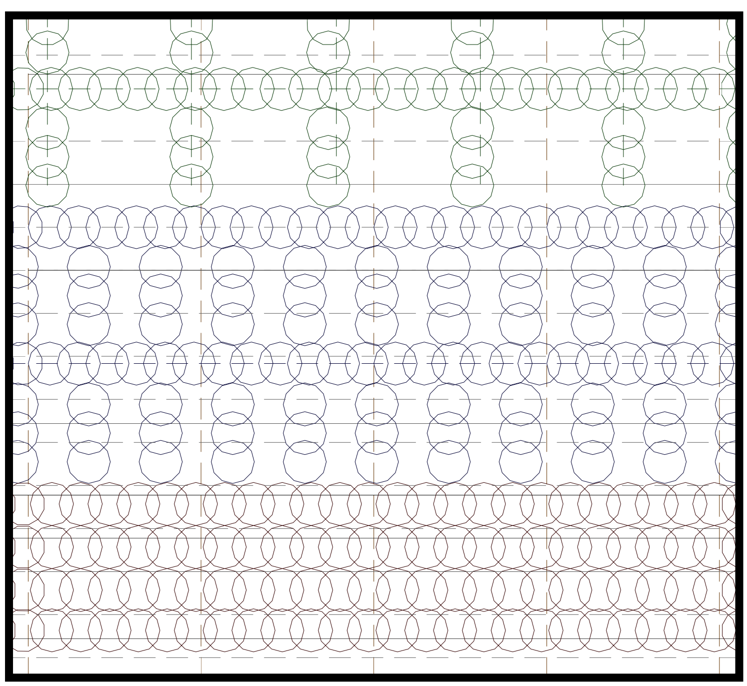
Figure 14b: Geometric Design

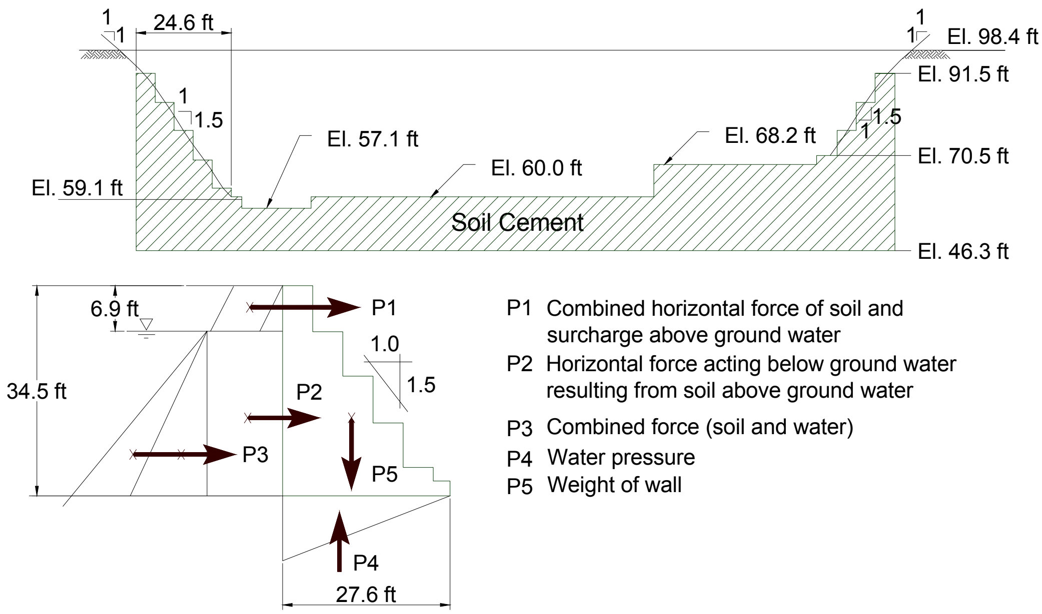

Figure 15: Cross Section A-A (Courtesy of Bechtel Corporation & EERI)

4. Wall Installation

Triple-axis soil mixing equipment was used to install soil-cement grids and gravity walls according to the layout design shown in Figure 14b. The construction began in April 2001 and was completed in October 2001. A total of 70,000 cubic yards of soil-cement was produced. A view of the CDSM gravity wall is shown on Figure 16.

Figure 16: A View of Excavated CDSM Wall and Foundation

V CONCLUDING REMARKS

In situ soil mixing methods provided efficient solutions for projects with challenging subsurface conditions. It produces reinforced soil-cement walls or gravity walls for effective earth retention and seepage control in difficult ground, including highly permeable cobble soils, soft soils, or liquefiable ground.

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