Stabilization Of Soft Soils By Soil Mixing

By Kenneth B. Andromalos[1], Yasser A. Hegazy[2] and Brian H. Jasperse[3]

Abstract

The use of soil mixing for providing stabilization of soft or loose soils is considered a fairly new technology in the United States. Soil mixing has been successfully applied for liquifaction mitigation, steel reinforced retaining walls, groundwater cutoff walls, and stabilization of contaminated soils. Applications of this technology have recently been further expanded. Such applications have included settlement control of soils, slope stabilization and the formation of composite gravity structures. To design for these applications, the unconfined compressive strength, elastic modulus and shear strength of the soil and soil-cement columns must be determined or estimated. Settlement control of soft or loose soils under service loads can be sufficiently controlled with treatment ratios in the 20% to 35% range. On a recent project in Honolulu, Hawaii, loose soils were sufficiently stabilized with a 23% treatment ratio, and at a site in Lakeland, Florida, a very soft and compressible clay layer was sufficiently stabilized with only a 12% treatment ratio. In slope stability applications, soil mixing improves the overall shear strength of the soil formation to adequately increase the factor of safety, and also the soil-cement columns can force the potential failure surface deeper. Lastly, soil mixing has been applied to construct in-situ gravity structures where its composite action design assumption was confirmed with an instrumented test wall, and used in two recent commercial applications.

Introduction and History

In the United States, soil mixing was first developed by Intrusion-Prepakt, Inc. of Cleveland Ohio in the 1950's (Liver et al. 1954) as "Intrusion Grout Mixed-in-Place Piles". In the late 1960's and early 1970's the Swedes used a mixed-in-place lime stabilization process (Ryan et al. 1989). In the 1970's, 1980's and today, the Japanese and Scandinavians continue to refine the soil mixing technology in various foundation applications.

[1] Regional Manager, Geo-Con, Inc., Monroeville, PA, USA, Email: kandromalos@geocon.net
[2] Project Engineer, D'Appolonia, Monroeville, PA, USA, Email: yahegazy@dappolonia.com
[3]President, Geo-Con, Inc., Monroeville, PA, USA, Email: bjasperse@geocon.net

Soil mixing was reintroduced into the United States by Geo-Con, Inc. in the late 1980's. Its applications were for liquifaction mitigation, steel reinforced retaining walls, groundwater cutoff walls, and stabilization of contaminated soils.

Soft and loose soils must be either bypassed by deep foundations, removed and replaced, treated for months or years by wick drains and pre-loading, or improved in order to build over them. The use of soil mixing for providing stabilization of soft or loose soils has not yet widely spread in the United States. Applications of this technology have recently been further expanded to include settlement control, slope stabilization and the formation of composite gravity structures in soft, loose and unstable soils.

Applications

Soil mixing is used in settlement control of soft soils supporting embankments, especially approaching bridges to control the differential settlement between bridge foundations and an embankment. It is also used to stabilize critical slopes and increase the overall factor of safety, and to form a composite gravity structure to support vertical excavations. This most recent patented application is also known as Vertical Earth Reinforcement Technology or VERT. Soil mixing provides satisfactory performance under both static and dynamic loads. However, only the static design of soil mixing is considered in this paper.

Soil mixing is used in several applications as a more economical or improved performance alternative to some traditional and other geosystem methods. These other systems include augercast piles; stone columns; jet grouting; compaction grouting; wick drains/preloading; lightweight fills, and conventional retaining walls.

In settlement control applications for embankment or structure foundations in very soft soils, soil mixing is sometimes preferred over stone columns. Stone columns may not being technically feasible due to inadequate lateral support, or may be cost prohibitive due to the unavailability of appropriate aggregates. When compared to the use of wick drains and preloading, soil mixing permits an accelerated construction schedule and eliminates the cost of hauling in additional fill for the replacement of settling subsoils, and permits the construction of steeper embankment slopes, while maintaining the necessary slope stability safety factors.

Installation

In-situ soil mixing is accomplished using either single shaft or multiple shaft drilling equipment. The mixing tools consist of hollow-stemmed shafts that have one or a series of discontinuous auger flights. Between the auger flighting, thick flat beater bars are attached. At the bottom of each shaft is an earth auger cutting head.

During drilling, the cutting heads penetrate the soil as a cement-based grout is pumped as a drilling fluid through the hollow stem and out the tip of the shaft. The discontinuous auger flight loosens and breaks up the soil but does not lift it out of the holes as continuous auger flighting would, but rather lifts the soil to the flat bars which mixes the grout and soil in a pugmill fashion into a homogenous soilcrete column. In high water content soils where a drilling fluid is not necessary, dry cement may be injected to reduce the total amount of cement required to achieve desired strengths. However, a majority of the applications utilize a fluid grout.

Strength Properties of Soil Mixing

The strength properties of cured soil-cement (soilcrete) elements necessary to perform design include Unconfined Compressive Strength (C_u), Elastic Modulus (E) and Shear Strength (τ). These strength properties are usually obtained by performing unconfined compressive strength tests of a specific mixture and they are function of the water to cement ratio of the grout (typically 0.9 to 1.3 by weight), grout injection volume (typically 20% to 40% of the soil volume) and the dry cement to soil ratio (typically, 200 to 450 kg/m^3). Typical values of soil-cement strength properties are summarized as follows (FHWA-SA-98-086):

$$C_u = 10 \text{ to } 50 * C_{u\ (soil)} \text{ (kPa)} \quad (1)$$

$$E = 50 \text{ to } 200\ C_u \quad (2)$$

$$\tau \approx 0.5\ C_u \quad (3)$$

The upper limits of shear strength properties are usually obtained for higher cement ratio and/or cohesionless soils and the lower limits are usually obtained for lower cement ratio and/or cohesive soils. The composite properties of the soil-cement elements and the surrounding untreated soils are a function of the treatment ratio (α) (ratio of the volume of treated soil to the volume of the soil mass), which is generally ranging between 20% and 35%. For instance, a composite modulus (E_c) is the weighted average of the soil and the soil-cement modulus is as follows:

$$E_c = E_{soil} * (1-\alpha) + E_{soil\text{-}cement} * \alpha \quad (4)$$

Soil Mixing for Settlement Control

Soil-cement columns are used to reduce the potential total settlement of soft soils under service loads. The total time required to complete reduced settlement will be less. However, the rate of settlement of a composite material usually remains similar to the original soil because soil-cement columns have a permeability about the same as for the in-situ soil. Soil-cement columns form a composite material with untreated soils and applied loads are proportionally distributed between them based on their relative strength and α. The upper limit of α is 78.5% for tangential soil-cement columns, where applied vertical loads are only carried by soil-cement columns. The lower limit of α can be adopted to equal 8.7% corresponding to a soil-cement column-spacing of 3 diameters, which is usually recommended to minimize the interaction (composite action) between deep foundation elements such as piles. Typical values of α are equal to 20% to 35%. Lin and Wong (1999) applied soil-cement columns to control the settlement of a trial embankment on soft clay. They used α of 20% (2-diameters center to center spacing) and geogrid layers for more uniform distribution of applied vertical stresses. Based on field measurements, the load distribution ratio between the soil-cement columns and the soft soil was approximately equal to 5 (80% of the loads taken by soil-cement columns). A hard layer (cap) of mixed cement and soil spoil and/or geogrid reinforcement layer(s) at the top of the soil-cement columns help to uniformly distribute the vertical loads. One dimensional-settlement of composite material is determined using elastic theory. Lin and Wong recommended using the following formula to estimate the total settlement:

$$S = (P * H) / E_c \quad (5)$$

in which, S is estimated total settlement, P is an applied vertical stress, and H is a layer thickness. Bergado et al. (1990) recommended using the following expression for prediction of the total settlement considering the effect of confining stresses:

$$S = \Sigma H * (\Delta\sigma_z - \nu * (\Delta\sigma_x + \Delta\sigma_y)) / E_c \quad (6)$$

in which, $\Delta\sigma_z$ is the vertical applied stress, ($\Delta\sigma_x$ and $\Delta\sigma_y$) are the applied stress components in the horizontal plane, and ν is Poisson's ratio. Using the latter expression requires measuring or estimating ν and the at-rest horizontal coefficient of earth pressure (K_o). Settlement design using soil-cement includes determination of an appropriate α and E for settlement control and C_u for determination of compression capacity of soil-cement columns.

Soil Mixing for Slope Stabilization

In the case of critical slope stability, driving forces due to lateral earth pressure and water pressure, if any, are almost equal to resisting forces due to soil weight and soil shear strength. Using continuous soil-cement columns (one or more rows) near the toe of a slope to intersect a potential failure surface improves combined shear strength (τ_c), which increases the factor of safety. Soil-cement columns can force the potential failure surface below column tips, thus increasing both resisting force due to soil weight and factor of safety. Soil-cement columns should be designed to determine an appropriate τ value to provide an adequate internal shear resistance of soil-cement columns to overcome soil and water lateral pressures and to achieve the design safety factor.

Soil Mixing for Vertically Earth Reinforced Technology (VERT) Wall

A VERT wall is a new type of top-down retaining wall, which has been developed to be cost effective relative to tieback walls and soil nailed walls. The VERT wall is a gravity wall; therefore it usually does not require internal or external reinforcement. Except in some cases, light steel reinforcement may be used in some of the front face columns to provide anchorage for permanent cast in place facing.

The VERT wall system typically consists of a continuous front row of soil-cement columns and one or more rows of isolated soil-cement columns or staggered soil-cement panels. The VERT wall is a gravity soil-cement system that supports a vertical excavation. Based on analyses completed, the following typical parameters have been arrived at. The width of the wall supporting dry or partially saturated soils is 0.6 to 0.8 the wall height. The width of the wall increases due to higher water pressure (shallow water table). A minimum soil-cement column toe of 1 to 1.2 m is recommended. Where possible, the surface soilcrete spoil should be used to tie the soil-cement columns as a cap at the top of the wall. The columns edge-to-edge spacing should not exceed 1.2 to 1.5 times a column diameter to ensure internal integrity and development of composite action between the wall elements. A treatment ratio is typically 20% to 35%. Actual design parameters should be confirmed on a case by case basis.

The VERT wall should be designed for external and internal stability. External stability includes sliding, overturning, bearing capacity, settlement and global stability. An active earth pressure is assumed for the design, which should satisfy the following minimum factor of safeties: 1.5 for sliding, 1.3 to 1.5 for overturning and 1.5 for overall global stability. Bearing capacity is usually not a problem because the unit weight of soil-cement columns is usually similar to that of the original soils, however the base of the wall should be in compression. Tolerable settlement is recommended to be based on bearing capacity requirements. Internal stability includes development of composite action to obtain a gravity structure, adequate soil and soil-cement column shear capacity, minimizing soil and columns tensile stresses and limiting wall face deformations. Typical required parameters for the design of the VERT wall system are C_u, E and τ. The shear, axial compression and axial tension stresses should be checked at critical sections under applied service loads and a minimum factor of safety of 1.5 should be obtained for each design mode. Based on our experience, soil-cement column tensile strength is approximately equal to 10% of its unconfined compressive strength. The soil extrusion pressure, development of composite action and wall face deformation are checked using finite element techniques, based on which the above wall geometry recommendations were developed (Nicholson et al., 1998). Currently, the development of a simplified design method is being considered to minimize or eliminate the need for finite element analysis in typical design applications.

Case Histories

VERT Test Wall, College Station, Texas

In order to demonstrate the viability and study the behavior of the VERT wall, a full scale, instrumented wall was constructed at the National Geotechnical Experimentation site (NGES) at Texas A&M University. The wall was 10 m high, 40 m long, and 5.6 m wide (Figure 1).

Prior to construction, three peer reviewers, Jean-Louis Briaud of Texas A&M University, James K. Mitchell of Virginia Tech University and Thomas D. O'Rourke of Cornell University, predicted the behavior of the VERT wall. Based on long-term monitoring, the actual movement was within the predicted ranges, thus confirming basic design parameters.

Instrumentation included survey control points, horizontal and vertical extensometers, and inclinometers. Texas A&M University collected the long-term readings of the instrumentation, reduced the data and analyzed the results. After over a year of monitoring, total horizontal movement was less than 30 mm and all portions of the wall moved together, thus confirming composite action of the soil-cement elements within the soil. A maximum 3-mm difference in readings was measured between the front and rear face of the VERT wall.

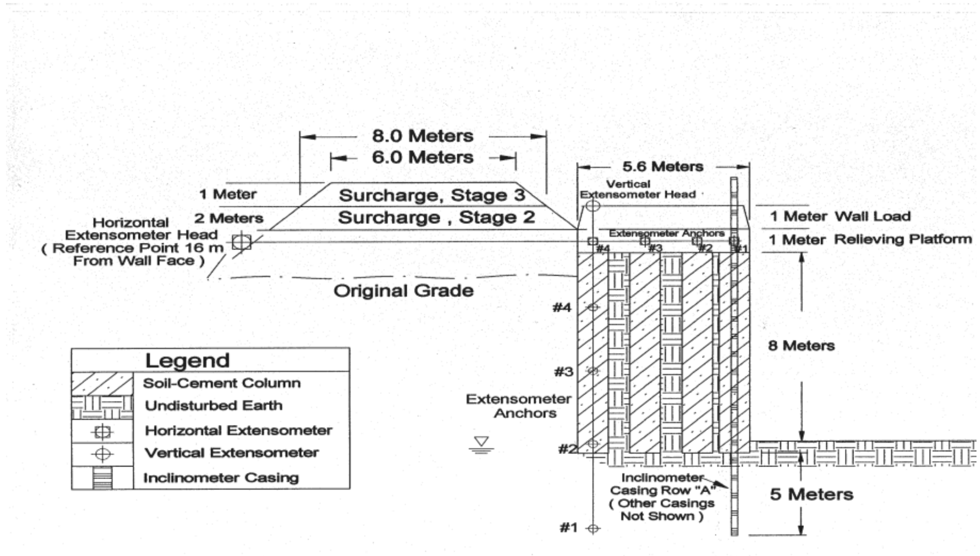

Figure 1. Cross Section of VERT Wall at College Station

<u>VERT Wall and SOIL-CEMENT Ground Improvement</u>
<u>Lakeland - Polk County, Florida</u>

The area in the vicinity of the site has been mined for phosphate for many decades. Mine tailings were deposited into pre-excavated trenches, including at this site. Accordingly, the site stratigraphy includes a mixture of natural soils and interbedded layers of very soft and compressible clays (colloidal clay slimes) that were produced during processing of phosphate. The soils at the site were classified as sand with silt or clay (SP, SP-SM and SC) and occasional thin layers or seams of clay with high plasticity (CH). The ground water table (GWT) was almost 1 m below the ground surface (GS). Clay slimes were encountered inside and outside the parcel along the southeastern corner, where an entrance road and parking lot were planned. Pockets of clay slimes were found 4 m below the GS in the parking lot area, which indicated potential settlement due to applied loads. Larger pockets of clay slimes were found 5.7 m below the GS at the entrance road and southward of the property line. The clay slimes located in the next parcel to the site is likely to be removed by making vertical cuts, which would affect the stability of the entrance road and possibly the parking lot. Therefore, a VERT wall system was proposed to provide an economical support for the vertical excavation and area treatment by soil mixing beneath the proposed parking lot was proposed to minimize settlement potential. Figures 2 and 3 show plan and elevation views of this combined application. The finished pavement surface (FPS) was proposed 0.91 m below existing GS.

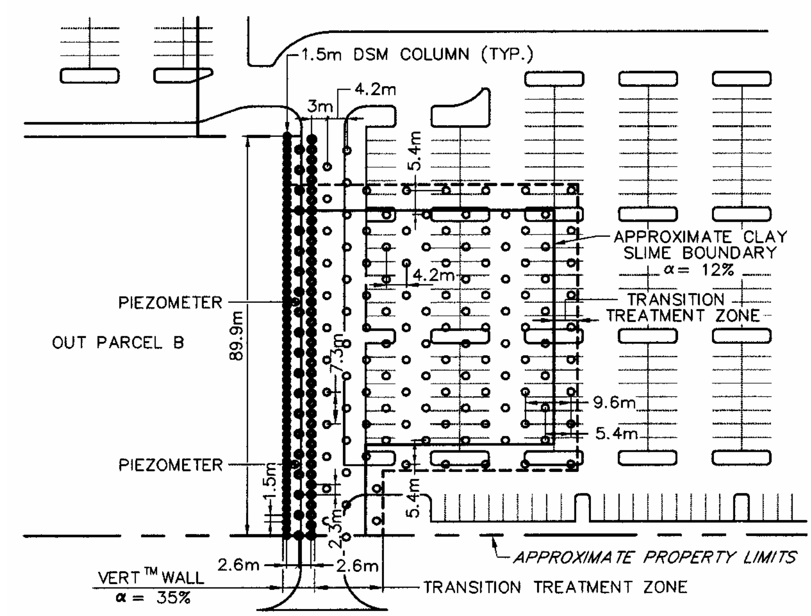

Figure 2. A Plan of Soil Cement Columns and VERT Wall Lakeland – Polk County, Florida

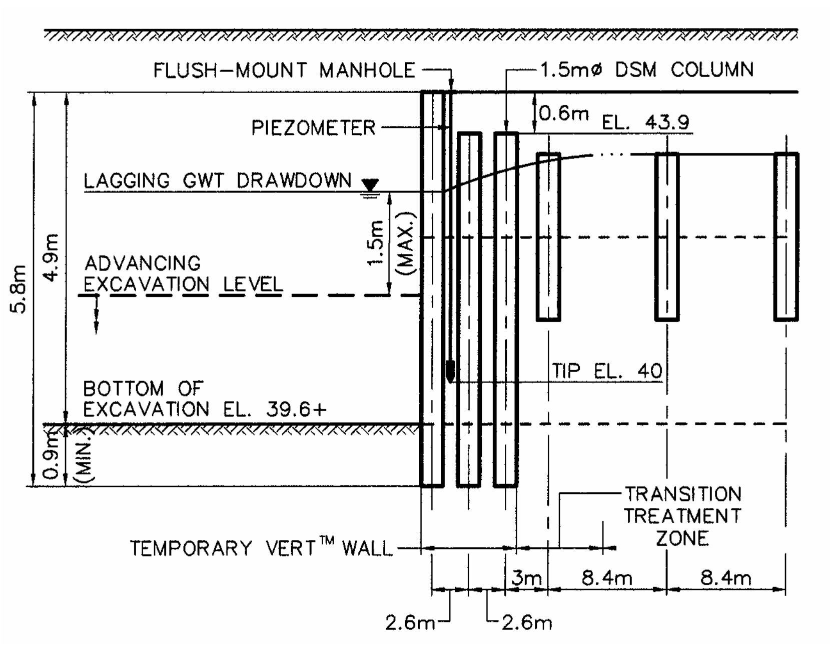

Figure 3 A Cross Section of Soil Cement Columns and VERT Wall Lakeland – Polk County, Florida

The VERT wall was designed considering a maximum supported excavation height of 4.9 m, and a soil-cement column diameter of 1.5 m with a minimum embedment of 1 m. The VERT wall consists of 3 rows, where the soil-cement columns of the first row are continuous and that of the two back rows are staggered. Applied loads included active earth pressure, static water pressure and a surcharge pressure. Soil shear strength parameters were determined using in-situ testing including piezocone test and standard penetration test data. External stability of the VERT wall was performed, and by iterating, a wall width equal to 6.7 m provides an adequate performance of the VERT wall. For sliding, overturning and global failure, a factor of safety greater than 1.5 was obtained for each design mode, and the entire wall base was in compression.

The VERT wall internal stability was checked to confirm the maximum compression, tensile and shear stresses in the composite section of the soil and soil-cement columns. A satisfactory structural performance was achieved and a factor of safety greater than 1.5 was obtained for each critical design mode considering the following: (1) minimum soil mixture unconfined compressive strength (C_u) = 1000 kPa, and (2) minimum replacement ratio (α) = 35%. In conjunction with the VERT Wall construction, two piezometers were recommended to be installed immediately behind the front row of columns to monitor ground water drawdown during excavation in the out parcel. The ground water level behind the front face of the VERT Wall was considered to be drawn down as the excavation was advanced and dewatered (e.g., with sump pumps). The rate of excavation was controlled to allow time for this drawdown to occur, such that a plane of significant hydrostatic pressure did not develop against the front row of columns. Accordingly, the excavation level could not advance more than 1.5 m ahead of the ground water level observed in the piezometer installations.

The settlement potential was assessed for the proposed parking lot behind the VERT Wall, and the approximate area and depths of clay slimes were delineated. By reviewing the proposed construction and the available boring logs for the area, it was determined that the existing grades were generally 1 m higher than the proposed final grades. This suggests there was a small net reduction in load over the parking area. However, a significant surcharge load over the subject area was considered due to storing, stockpiling or displaying inventory. Also, future ground water drawdown, such as during the removal of adjacent clay slimes and local dewatering in front of the VERT wall, the looser consistency of the shallower soils, and possible ongoing consolidation of the clay slimes were considered to determine the settlement potential at the site.

Due to the above factors, the clay slimes experienced a stress increase of approximately 13.4 kPa at a depth of 3.1 m below the final pavement surface. This is equivalent to a ground water drawdown of 1.4 m, or to a modest increase in surface load such as from fill placement or surcharges.

For a clay slimes thickness of 1 m, the estimated settlement was equal to 64 to 75 mm from consolidation of the clay slimes if left untreated. For comparison, soil-cement treatment of the clay slimes and the shallow overburden soils at a ratio of approximately 12% would negate 85 to 90% of this settlement (i.e., estimated settlement over treated area = 8 to 13 mm). Also, the soil-cement would improve the subgrade stability, which may be a concern due to the high ground water levels and/or looser consistency of the shallower soils. Therefore shallow soil mixing was beneficial in stabilizing the shallower soils to mitigate settlement from consolidation of the clay slimes, and to prevent accelerated deterioration of the pavement from rolling and pumping over wet, loose subgrade.

The soil-cement activities generate excess spoil that is beneficially altered by cement-slurry. Therefore, the soil-cement spoil is anticipated to have better strength properties and be less affected by the high ground water levels than the upper, loose soil underlying the future pavement area. Accordingly, the existing subgrade soils beneath the planned pavement level could be overexcavated 0.5 to 1 m, and then be replaced with the soil-cement spoil to improve subgrade stability and better distribute the surface loads to the soil-cement columns. Alternatively, the soil-cement spoil could be used as backfill when reclaiming areas of clay slimes removal, such as in front of the VERT wall.

Sand Island – Ground Improvement for Above Ground Storage Tank Foundations
Honolulu, Hawaii

On this project, soil mixing was used to improve the bearing capacity of the foundation soils, and control settlement of three large diameter above ground petroleum storage tanks (Bahner et al., 2000). These tanks had been constructed on sandy lagoonal deposits and adjacent to existing tanks within an existing facility. The original ground improvement design called for 0.9-m diameter stone columns to bedrock on a 2.75-m spacing. The alternate soil mixing design consisted of 1.8 m diameter soilcrete columns on a triangular grid pattern with a treatment ratio (α) of 23% (Figure 4). This alternate design was selected by the designer due to the following advantages:

- Cost;
- Soil mixing did not generate significant vibrations, thus eliminating potential damage to surrounding tanks;
- The soils requiring improvement were contaminated with diesel fuel and the soil mixing method resulted in solidified spoils, thus eliminating off-site disposal and preventing material leachability;

- The solidified excess soils provided material to construct a soil-cement relieving platform, thus eliminating the need for importing an aggregate structural fill beneath the proposed foundation, and
- Unlike stone columns, the soil mixing alternative resulted in a smaller treatment area, which did not need to extend beyond the perimeter of the tank ring walls.

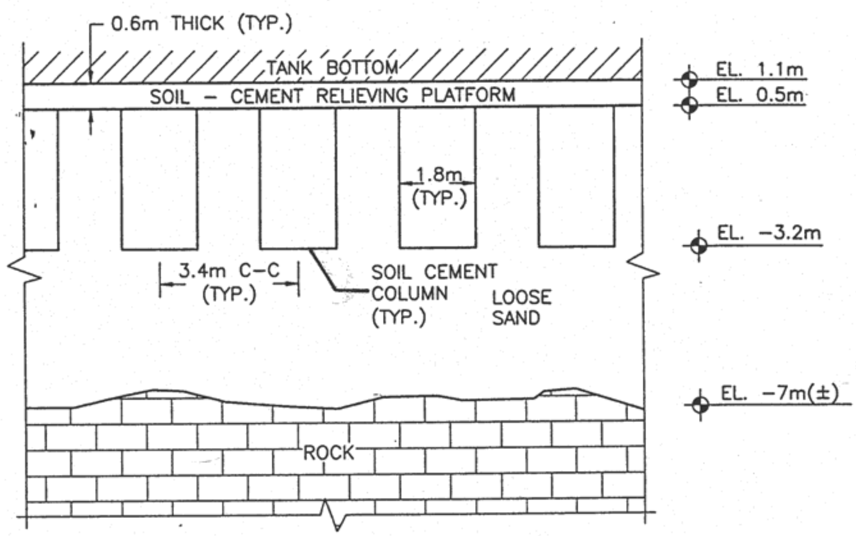

Figure 4. Cross Section of Soil Cement Columns at Honolulu, Hawaii

After construction, the new tanks were hydrostaticly tested in accordance with American Petroleum Institute (API) Standard 650 requirements. The results of this testing confirmed that settlement was within allowable limits set forth by API and the settlement measured was 50% to 70% less than adjacent similar tanks on untreated ground.

Conclusions

Soil mixing has been applied to provide improvement and stabilization of cohesive and cohesionless soils under static loads. Soil mixing is a fairly new technology in the United States. A primary concept is to enhance the soil strength and elastic properties by forming an integrated matrix of soil-cement columns and the original soil. A treatment ratio is typically 20% to 35%. Three case histories of soil mixing to provide resistance to static loads were illustrated in the paper. Soil cement columns have been used to stabilize soft cohesive and loose cohesionless soils for control of their movement. Soil mixing has been conducted to form gravity retaining structures including, VERT wall, usually composed of continuous columns at the front row and staggered columns at the back rows. External stability of the VERT wall must be checked against sliding and overturning. Bearing capacity is also evaluated making sure that the wall base is primarily in compression. The performance of the VERT wall at Texas A&M, NGES site was verified to be satisfactory using in-situ measurement of the internal stresses and vertical and horizontal deformations of the wall.

References

Bahner, Eric W., Naguib, Aiman M. (2000). “Ground Improvement for Large Above Ground Petroleum Storage Tanks Using Deep Mixing”, GEODENVER 2000, Denver, CO, in press.

Bergado, D.T., Ahmed, S., Sampaco, C.L. and Balasubramaniam, A.S. (1990). “Settlement of Bangna-Bangpakong Highway on Soft Bangkok clay”, *Journal of Geotechnical Engineering*, ASCE, Vol. 116, No. 1, 136-155.

Ground Improvement Technical Summaries (1998). Federal Highway Administration, U.S. Department of Transportation, Working Draft, No. FHWA-SA-98-086, Vol. II., in press.

Lin, K.Q. and Wong, I.H. (1999). “Use of deep cement mixing to reduce settlements at bridge approaches”, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 125, No. 4, 309-320.

Liver, Norman L., Mardorf, Erwin C., King, John C. (1954). “Development and Applications of Intrusion Grout Mixed-in-Place Piles”, *Civil Engineering*, March 1954, 56-57.

Nicholson, P.J., Mitchell, J.K., Bahner, E.W. and Moriwaki, Y. (1998). “Design of composite gravity wall constructed by soil mixing”, Soil Improvement for Big Digs, *Geotechnical Special Publication*, ASCE, No. 81, Boston, MA, October, 27-40.

Ryan, Christopher R., Jasperse, Brian H. (1989). “Deep Soil Mixing at the Jackson Lake Dam”, ASCE Geotechnical and Construction Divisions Special Conference, Evanston, IL, June 25-29, 2.