GROUND IMPROVEMENT FOR LARGE ABOVE GROUND PETROLEUM STORAGE TANKS USING DEEP MIXING

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ABSTRACT: The Bearing Capacity and Settlement behavior of large diameter above-ground petroleum storage tanks are critical in loose and soft soils. On Sand Island in Honolulu, Hawaii, there is a history of large magnitudes of settlement associated with these types of tanks. On a recent tank expansion project, large diameter Soil-Cement Columns constructed using In-situ Deep Mixing were used to improve the bearing capacity and control the settlement of three large diameter storage tanks constructed on sandy lagoonal deposits. Although the settlement of the tanks exceeded predicted values, the Deep Mixing Ground Improvement Program successfully limited settlement to within the specified and allowable values. Furthermore, Deep Mixing also provided cost effective means of treating petroleum-impacted soils at the tank locations.

INTRODUCTION

As a result of increased demand for additional fuel storage capacity due to on-going expansion at the Honolulu International Airport, a proposal for expanding the Sand Island Fuel Storage Facility was implemented. Part of the expansion program for the facility, which is located approximately 4 miles southeast of the airport, called for the installation of three large diameter above-ground fuel storage tanks. Since the tanks were to be constructed on loose sandy soils, and given the past settlement history of tanks constructed adjacent to this site, the project designers required the subsurface soils underneath each proposed tank location to be improved using stone columns in order to limit tank settlement and increase the bearing capacity of the soils. An alternate proposal for the subsurface soil improvement was submitted by Geo-Con, Inc. This proposal called for installing soil-cement columns using In-Situ Deep Mixing. The alternate proposal was ultimately selected by the Designer due to many advantages including the following:

- Cost-effectiveness of the deep mixing method.
- The deep mixing method does not generate any vibrations, thus eliminating the potential for damaging surrounding structures.

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- The soils requiring improvement were contaminated with diesel, Jet A fuel, and aliphatic and alicyclic hydrocarbons. As such, the deep mixing method provided a way to solidify the spoils resulting from construction. This eliminated off-site disposal and prevented material leachability.

- The alternate design called for the spoils resulting from construction to be blended with additional cement and utilized in constructing a 2-foot relieving platform over the soil-cement columns. In doing so, the need for placing imported structural fill and a 12 oz. non-woven geotextile fabric underneath each tank shell was eliminated.

- Unlike stone columns, the deep mixing method provided a way to meet the performance requirement without extending the soil treatment area 1.5 meters beyond the perimeter of each Tank Ring Wall.

PROJECT DESCRIPTION

The project consisted of constructing three large diameter, above-ground fuel storage tanks over improved subsurface soils. Two of the tanks (Tank Nos. 6 and 7) had a diameter of 31 meters and a height of 14.6 meters. The third tank (Tank No. 19) had a diameter of 27.4 meters and a height of 9 meters. A concrete ring wall with a combination of compacted crushed stone and sand fill including two layers of non-woven Geotextile fabric made up the original foundation design. See Figures 1, 2 and 3 for more details regarding tank locations and associated design.

SUBSURFACE CONDITIONS

The subsurface conditions below the new tank locations typically consists of 1 to 1.2 meters of silty sand and gravel fill over several feet of clay sand to sandy clay. The clay sand/sandy clay is underlain by loose to dense lagoonal sands. Moderately strong to strong coralline bedrock is present below the sands at depths of 7.6 to 9.75 meters. A typical soil profile is presented in Figure 4.

DESIGN ASSUMPTIONS AND CRITERIA FOR POST-SUBSURFACE SOIL IMPROVEMENT

- Allowable Bearing Capacity = 239 kPa (5,000 Psf.)

- Maximum Allowable Settlement:

LOCATION	TOTAL SETTLEMENT, mm (in.)		DIFFERENTAL SETTLEMENT, mm (in.)	
	CENTER	EDGE	CENTER TO EDGE	EDGE TO EDGE
TANK NO. 19 90' Diam x 60' Ht	318 (12.50)	178 (7.00)	140 (5.50)	83 (3.25)
TANK NOS. 6,7 102'Diam x 48' Ht	279 (11.00)	159 (6.25)	133 (5.25)	76 (3.00)

DEEP MIXING FOUNDATION DESIGN

The project specifications required that the design provide a minimum bearing capacity of 239 kPa and limit settlements to within the criteria identified earlier in this paper. Bearing capacity was estimated assuming a 2-layered system using the Terzaghi bearing capacity equation. Soil properties were estimated from the available soil boring data, and standard penetration tests blow counts. The shear strength of the soil-cement was estimated as ½ the unconfined compressive strength. The impact of the foundation loads transferred to the individual loads on the individual soil-cement columns was considered using standard drilled shaft concepts.

Settlement was estimated using common elastic solution provided in most foundation engineering text books using an estimated modulus of 200 times the unconfined compressive strength ($E=500\ q_u$) for the soil-cement, and E=6N for the untreated sandy soil. Assuming a design soil-cement strength of 1379 kPa (200 psi), a soil-cement modulus of 689 MPa (7200 tsf) was estimated. A modulus of 3.4 Mpa (36 tsf) was estimated for the untreated soil assuming an average standard penetration test value of 6 blows per 0.3 meters. As a check, the modulus for the untreated soil was back-figured using settlement data for similar above ground tanks constructed immediately adjacent to the new tanks. The result of that analysis resulted in a 3.1 Mpa (32 tsf) modulus value, similar to that calculated using standard penetration test data.

Using the estimated soil and soil-cement moduli, it was determined that the specified bearing capacity and settlement criteria could be satisfied using a 23% replacement (treatment) ratio, and 3.7 m long columns. The 23% replacement ratio translated to a pattern of 1.8 meter diameter columns below the footprint of each tank at spacings of 1.0 to 1.7 times the soil-cement column diameter. The columns were terminated short of bedrock to avoid overstressing the columns, and because the settlement criteria was satisfied at treatment depths of 3.7 meter. The predicted settlement for each of the 3 tanks is tabulated below.

Tank Number	Settlement (m)		
	Diam.(m)	Edge	Center
19	27.4	76-114	114-165
6,7	31	51-76	76-102

Figures 5, 6, and 7 illustrate the selected treatment pattern below each of the tanks.

CONSTRUCTION PROCEDURES

The in-situ soil mixing system utilized for the project consisted of two components. The first component was the soil mixing system itself. This component was made up of a crane-mounted turntable which rotated a hollow Kelly Bar with a 3.7 meter diameter auger/mixer. The second component of the system was the reagent mixing batch plant and delivery system. This consisted of two 3.8 cu. meters high-shear lightning mixers. The first mixer was used for cement grout preparation and the second mixer was used for circulation and storage.

Cement grout was prepared by blending Type I Portland cement with fire hydrant water using a cement to water ratio of 1.0 to 0.75 by weight. Due to the relatively small size of the project, a dry cement metering system was not installed at the batch plant. Instead, dry cement was delivered in "Super Sacks" with known weights. These known amounts of Cement were added to a metered volume of water to insure compliance with the Grout Mix Design. See Figure 8 for a Schematic of Geo-Con's Batch Plant.

Upon Grout preparation, the resulting mixture was conveyed to the Kelly Bar of the soil mixing rig using a positive displacement pump. The Grout was then dispersed into the soil through the auger/mixer's grout dispersion points. As the auger/mixer rotated, the grout was pumped and mixed with the in-situ soils. The auger/mixer's continued rotation and downward movement provided homogeneously mixed soil-cement columns. Cement grout injection into the soil was monitored through a flow meter to insure compliance with the mix design which called for adding 13% cement to soil by weight. Such a mix design insured that the required 200 psi (in 28 days) unconfined compressive strength for the soil-cement mixture was met. Refer to Figure 9 for a schematic of Geo-Con's soil mixing rig.

The soil-cement relieving platform was constructed by adding known amounts of cement grout from the batch plant to borrowed on-site soils and soil-cement spoils. Mixing of the various components was done using a conventional hydraulic excavator over the top of the completed soil-cement columns. To insure that the required amount of cement to soil has been added, the areas over the soil-cement columns were divided into predetermined grid sections. These grid volumes received a predetermined volume of grout in accordance with the mix design program.

CONSTRUCTION MONITORING

The prepared soil-cement mixture was monitored during construction to insure that the specified unconfined compressive strength was achieved. This consisted of obtaining "wet" remolded soil-cement samples for unconfined compressive strength testing. The samples were obtained at various locations and depths from the soil-cement relieving platform and in-situ mixed columns. Unconfined compressive strength testing was performed on collected samples after 3, 7, and 28 days of curing. The results obtained after 28 days were typically one and a half times the 200 psi design strength. See Figure 10 for average unconfined compressive strength results after 3, 7, and 28 days of curing.

"Wet" soil-cement samples were collected from desired locations using the sampling tool shown in Figure 11. This tool consisted of a steel tube that suspends a sampling bucket along its bottom. The bucket is hydraulically opened and closed as needed. In areas where sampling is required, the steel tube is suspended by a hydraulic excavator and lowered through the freshly mixed soil-cement mixture to desired depth. At this point, the sampling bucket is hydraulically opened, thus filling itself with freshly mixed soil-cement material. The bucket is then closed and the tube retrieved. Grout molds were used for casting grout samples. The samples were placed in air-tight containers with wet paper towels for storage until the testing time was reached. Additionally, the cement grout's unit weight was measured at the batch plant using a mud balance to maintain each mixed batch's consistency within the mix design's unit weight tolerances.

POST-CONSTRUCTION MONITORING

The new tanks were hydrostaticly tested in accordance with American Petroleum Institute (API) Standard 650 requirements during the months of February and March, 1999. The tanks were tested in sequential order beginning with Tank No. 6 followed by Tank Nos. 7 and 19. Sea water from the nearby Keehi Lagoon was pumped into Tank No. 6 and was reused for the tests for Tank Nos. 7 and 19. Tank Nos. 6 and 7 were filled to a height of 45-ft while Tank No. 19 was filled to a height of 48-ft. Each tank was filled in 5 filling increments of approximately 8-to 10-ft. Each filling increment was held for approximately 12 hours before adding the next increment. After the tanks were filled to the target level, the water was held for at least 72 hours before being transferred to the next tank or discharged. The water levels were measured and recorded at the beginning of each elevation survey.

Settlement was measured using a series of survey points established on the top of the tank ring walls prior to testing. Twelve optical survey points were established for Tank Nos. 6 and 7, and 10 points for Tank No. 19. Spot elevation measurements were made at the beginning and end of the first two filling increments, and at 3 hour intervals for the remaining increments for each tank. During the final holding period survey measurements were made at the beginning and end of each working day. The measured settlement at the edges and centers of existing tanks Nos. 11 through 14 which were constructed on untreated ground ranged from 8 to 11 inches, and 10 to 23 inches, respectively. Measured settlement of the new tanks constructed on improved ranged from 7.6 to 8.6 inches at the center and 5.4 to 5.7 inches at the edge. The results of the hydrostatic testing program are summarized in the table below.

SETTLEMENT TYPE	TANK NO. 19		TANK NO. 6		TANK NO. 7	
	API ALLOWABLE	MEASURED	API ALLOWABLE	MEASURED	API ALLOWABLE	MEASURED
Uniform Settlement	18	3.43	18	4.19	18	4.56
Planar Tilting	5.4	4.55	6.1	3.58	6.1	1.73
Out-of-plane	1.09	0.21	1.22	0.39	1.22	0.25
Center to Edge	11.5	5.00	13.0	2.23	13	3.02
Localized Settlement	--	Not Observed	--	0.375	--	Not Observed

SETTLEMENT (INCHES)

CONCLUSION

In many cases, the actual measured settlements were greater than those predicted; however, the measurements were 50% less than those measured at the center, and 65% to 70% of the edge settlements measured for adjacent tanks constructed on untreated ground. The measurements fell within the limits identified in the project specifications, and the allowable limits set forth by API. Some of the variability observed in the results of the settlement measurements could be attributed to the variability of the subsurface conditions across the site. In general, the deep mixing method proved to be an effective means of improving the bearing capacity and compressibility of loose sandy soils below large diameter petroleum storage tanks. However, the limited amount of subsurface data reduced the accuracy of the bearing capacity and settlement predictions.

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