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Controlled Modulus Columns™ (CMC) for Support of Above-Ground Storage Tanks

Prepared for:
Ohio River Valley Soils Seminar XL (ORVSS)

November 13, 2009

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ABSTRACT

Controlled Modulus Columns™ (CMC) are pressure grouted auger displacement elements that are installed using a specially designed tool at the working end of a high torque, high down-pressure drilling machine. The tool is hollow so that flowable cementitious grout can be placed from the bottom up once the tool is advanced to the desired depth. The patented CMC system fits in the generic category of inclusions. There are a number of other types of inclusions that are currently designed and constructed using stone, grout, and concrete. The design technology and experience with CMC makes them uniquely efficient for the immediate support of large liquid or bulk solid storage tanks, as well as MSE walls and embankments for public transportation, other infrastructure facilities, buildings, and other structures.

Large-diameter, above-ground storage tanks impart heavy loads, deep into the ground, extending over a wide area. In many locations, the ground is stiff enough to safely support tanks without excessive settlement. However, many terminals, refineries and storage facilities are located along waterways and coastal plains in areas with soft compressible ground, or on uncontrolled fill that cannot safely support tanks. The support options in these areas have traditionally included: removing and replacing the existing soft ground; or installing deep foundation systems, such as piles with a concrete mat to support the tank.

CMCs are an ideal solution for the immediate support of large storage tanks. Using specialized drilling rigs, control of bearing layer penetration is provided in a consistent fashion, and electronic monitoring and recordation of drilling and grouting parameters is routinely used for quality control. The load is distributed to the CMC elements using a compacted granular load transfer platform that serves as an efficient and cost effective foundation. Other features such as leak detection and cathodic protection are detailed into the load transfer platform.

CMCs are designed using special proprietary finite element techniques that include the effects of load sharing between the distribution mat, the columns, and the surrounding improved ground. Special considerations for bearing into the distribution layer are made, as well as detailed designs for interaction with concrete or granular ring walls.

INTRODUCTION

Some amount of settlement occurs when any tank is built and put into service. The settlement is only problematic when it exceeds the tolerance for the tank or lines connected to the tank. The amount that a tank will settle is dependent on the tank loading properties (i.e., the diameter and the weight of the tank and its contents) and the soil properties (both elastic stiffness and long term settlement parameters) of the underlying soils. The settlement for similarly sized tanks at different locations may vary from an inch or less to 10 feet or more, depending on the range of ground conditions at the different locations. The amount that an individual tank settles is not always uniform for the entire tank as the substrata may vary significantly beneath the tank footprint. The tolerance that tanks have for differential settlement is significantly less than the tolerance for the maximum uniform settlement that can be withstood, with tanks that have floating roofs being the most sensitive to settlement.

In addition to excessive settlement, bearing capacity failure may occur where weak soils are present. This occurs when the underlying soils cannot carry the load from the tank and the ground shears or ruptures, causing either a rotation of the tank or punching of the tank into the ground. Although bearing capacity problems are less common than settlement problems, when bearing capacity failures occur, they are typically catastrophic in terms of the performance and servicability of the tank, with a very high risk of tank rupture and significant product loss. Failures occur when the weight of the tank induces stresses into the ground that the underlying soils are too weak to handle. Bearing capacity failures are rare, but when they do occur, may occur rapidly.

GROUND IMPROVEMENT FOR TANKS

Where weak soils are present in areas where tanks are to be built and it is not practical to change the location of the tanks, the weak ground can be replaced, bypassed with piles, or treated by a number of different ground improvement technologies. Removing and replacing soft ground with compacted backfill can be impractical or very costly when the soft ground extends below a few feet or if it is necessary to excavate below the groundwater table. At sites with very weak near-surface soils, the ground cannot safely support the construction equipment that is needed to excavate and haul away the soft soils. Installing piles to transfer the load from the tank to underlying bearing layers can be costly, and typically requires that a thick, heavily reinforced concrete mat be constructed to form a monolithic slab upon which the tank is founded. At some sites, the ground can be improved adequately just by surcharging the tank footprint (with a temporary pile of soil or by filling the constructed tank with water), and letting the weight of the surcharge consolidate the underlying soils. However, the surcharge process (in the absence of wick drains/prefabricated vertical drains) can take years or decades where the soils are slow draining.

For tanks, the goals of ground improvement are to reduce the total and differential settlement that occurs while tanks are in service, to increase the factor of safety against bearing capacity failure, and at some locales to reduce the risk that the soils supporting a tank liquefy during seismic events (i.e., earthquakes).

CONTROLLED MODULUS COLUMNS (CMCs)

Deep foundations are rigid structural elements that are used to transfer the load from the structure to competent layers below (bedrock, dense or stiff soils) by “bridging” the compressible soft soils. Because the loads are highly concentrated on the elements, the elements need to have direct contact with the structure to be able to transmit these loads either through end-bearing, skin-friction, or a combination of the two. Deep foundation systems are designed to allow minimal settlement and when used to support tanks, they require the use of a structural mat, or pile cap to connect the tops of the piles together to provide a foundation for the tank. The structural mats add significant costs to the project.

While more “deformable” ground improvement solutions (e.g., stone columns or aggregate piers) are often very economical compared to a deep foundation system, the expected and observed settlements are typically greater than that of rigid deep foundations. In the case of stone columns for example, the ratio of stiffness between the soil and the stone column determines the ratio of load shared between the soil and the element. Settlement is a factor of the stress carried by the stone columns and the soil and the respective compressibility of column material and the surrounding soil. Stone column design is based on the assumption that the column and the surrounding soil are compressed, or settle, equal amounts. When ground improvement is used, the load concentration in each element is significantly reduced as compared to a deep foundation system, and the structure need not be as rigid. With ground improvement, structures can be designed as if it they are founded on competent ground with a slab-on-grade and spread and strip footings, or in the case of storage tanks, using welded bottom plates and a peripheral ring wall without the need for a pile cap/mat beneath the tank.

Controlled Modulus Column™ (CMC) technology bridges the gap between these two different approaches (deep foundations and deformable inclusions) by reducing the global deformability of a soil mass using semi-rigid soil reinforcement columns. The soil–CMC mass behaves as a composite mass of greater stiffness than the initial untreated ground, reducing settlements induced by the weight of the structure to within allowable ranges. CMCs are not intended to directly support the loads imposed by the structure, but to improve the global response of the soil in order to control settlement. The dimensions, spacing, and composition of the CMCs are based upon the development of an optimal combination of support from the columns and the surrounding soil to limit settlements for the project within the allowable range, and to obtain the required value for the equivalent composite deformation modulus of the improved soil.

Some features of the CMC technology include:

- Material is grouted in place with the use of a displacement auger in order to reinforce the ground
- Deformation modulus of the CMC elements is 50 – 3,000 times that of the soil (weakest stratum)
- A load transfer platform of generally granular fill (LTP) is placed over the CMC reinforced ground that has a modulus less than that of the CMC elements which can be partially penetrated by the inclusions to promote strain compatibility/ load sharing between all the components
- In granular soils, densification due to the lateral displacement may occur between the columns by virtue of the displacement drilling process
- Virtually no spoils are generated by the drilling process which eliminates the need to manage spoils and the potential unearthing of contaminated soils

The tops of CMCs are typically installed 1 to 3 feet below the bottoms of the shallow foundations. A layer of compacted granular material referred to as the load transfer platform (LTP) is installed above the top of the CMCs and below the structure following installation of the CMCs. The main purpose of the LTP is to transfer the load from the structure to the CMCs without using pile caps between the structure bottom and the CMCs. The load is transferred to the CMCs through arching within the high phi-angle LTP and through side friction below the top of the CMCs. The system is generally designed to transfer 50 to 95% of the load to the CMCs while the remainder of the load is transmitted to the soils between the CMCs. The ratio of load sharing is dependent upon the type and stiffness of the soils between the CMCs as well as the allowable settlement for the structure.

The CMC technology is very well suited for very soft soil conditions such as organic clays, peat and wastes. Compared to stone columns that require a significant degree of lateral confinement to avoid bulging when loaded, CMCs have no such limitations due to the relatively high stiffness of the column material.

The installation of CMCs does not generate vibrations so the technology is ideally suited for construction in urban areas (working close to sensitive structures). CMCs are commonly used to support structures such as storage tanks, buildings, warehouses, industrial facilities, culverts and pipes, as well as platforms, embankments, retaining walls, and bridge abutments. The CMC columns typically range from 12 to 18 inches in diameter.

Installation of CMCs

CMCs are installed using a specially designed displacement auger that displaces the soil laterally without generating spoils or creating vibrations. The displacement auger is hollow, which allows for continuous placement of the grout as the auger is withdrawn. The grout for the CMC element is placed with enough back pressure to avoid collapse of the displaced soils during auger withdrawal (typically the static head of grout plus less than 100 psi is necessary). The installation process allows for the creation of a column with the diameter that is at least as large as that of the auger. CMCs are installed with drilling equipment that has large torque capacity and high static down thrust.

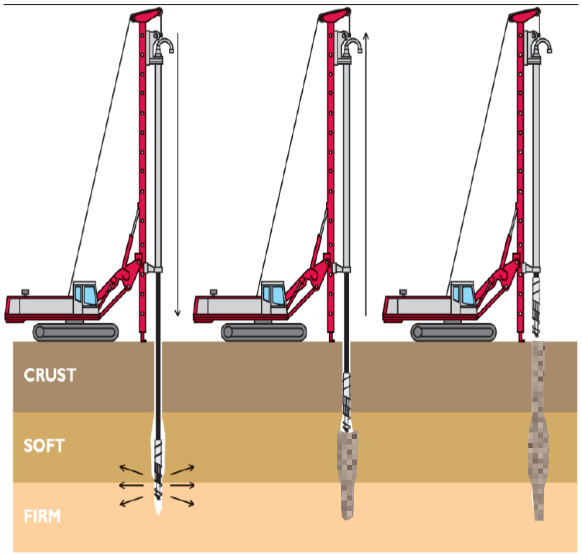


FIGURE 1 CMC installation schematic.

Upon reaching the desired depth, grout is pumped through the hollow stem of the auger and into the soil bore as the auger is withdrawn at a pre-defined rate that is calibrated to avoid necking.

With a conventional continuous flight auger, “negative displacement”, stress relief, or even lateral mining around the auger is inevitable. This creates a movement of the surrounding soils which are loosened by the augering process toward an active (Ka) condition. This condition creates a risk of necking. On the contrary, with the CMC displacement auger, the effect is opposite: the soil adjacent to the auger is displaced laterally by the displacement stem portion of the auger and brought to a denser passive (Kp) state of stresses. Stress relief does not occur and the risks of necking the CMC are quasi-inexistent, except with operator error.

Quality control of the CMC and monitoring to catch any operator error is done with real time monitoring of the following installation parameters:

- Speed of rotation
- Rate of advancement and withdrawal of the auger
- Torque, down-thrust (crowd) during the drilling phase
- Depth of element
- Time of installation
- Grout pressure in the line at the top of the drill string
- Volume of grout as a function of depth

The grout pressure is monitored by a sensor located at the top of the concrete line above the swivel attached to the mast drilling head. The CMCs are usually installed using a target overbreak of 5 to 10% of the volume of grout. During the grout phase, pressure readings are kept to a moderate positive pressure. Any loss in pressure can reveal a soft or loose soil zone that may not have been detected during the geotechnical investigation.

A significant benefit of the recordation of installation parameters is that changes in subsurface conditions can be detected in the field, and more importantly, column depths can be adjusted based on the encountered conditions as detected by the response of the drilling equipment. The recorded drilling parameters of down pressure, speed and torque are readily interpreted in the field during drilling and changes in stratigraphy can be sensed based on ease or difficulty of drilling. This ability to adjust column lengths in the field offers a significant advantage over most other forms of column installation.

Other forms of QC include monitoring fluid grout properties for consistency with the expectations of the design mix, and sampling, curing and testing of samples for grout strength. Load testing (ASTM D1143) is routinely done when there is no previous experience with elements capacities in the subject strata. Other in-situ testing such as PIT (Pile Integrity Tests) and dynamic loads tests (e.g. Statnamic) have also been used.

The CMC Design Concept

The behavior of an individual inclusion is predicated on reaching equilibrium under loads (Combarieu, 1988) as shown on Figure 2. While the inclusion is being compressed by the load, negative skin friction is acting in its upper part and positive skin friction in its lower part. When the equilibrium is reached, the stresses acting on the inclusion can be divided into four components:

- The vertical load, Q at the top of the inclusion
- The negative skin friction acting on the upper portion of the inclusion
- The positive skin friction acting at the lower portion
- The vertical reaction at the tip

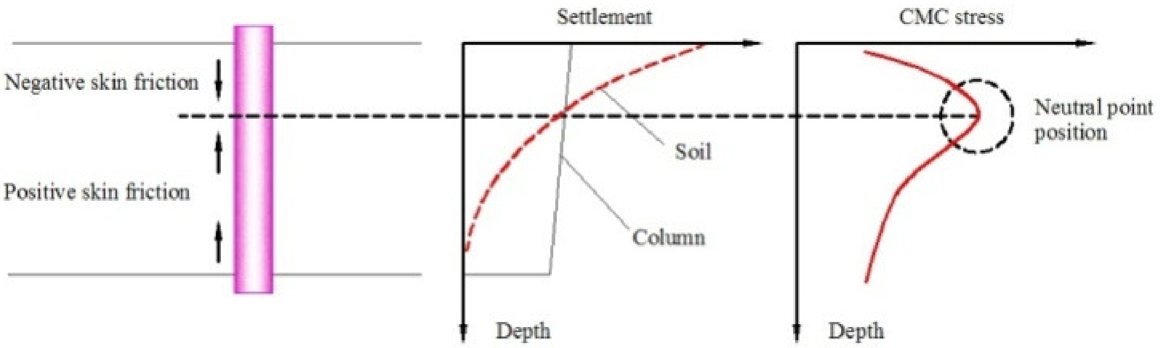


FIGURE 2 Settlement distribution between soil and an isolated inclusion.

The load of the structure is usually distributed to a network of inclusions by the LTP. Figure 3 shows how the load is distributed from the structure to the bearing layer. The load distribution between CMCs and surrounding soil is based on reaching an equilibrium between deformations of the CMCs and the surrounding soils. The design of a network of inclusions is thus based on a good knowledge of the distribution of stresses and deformations in the soil and the inclusions.

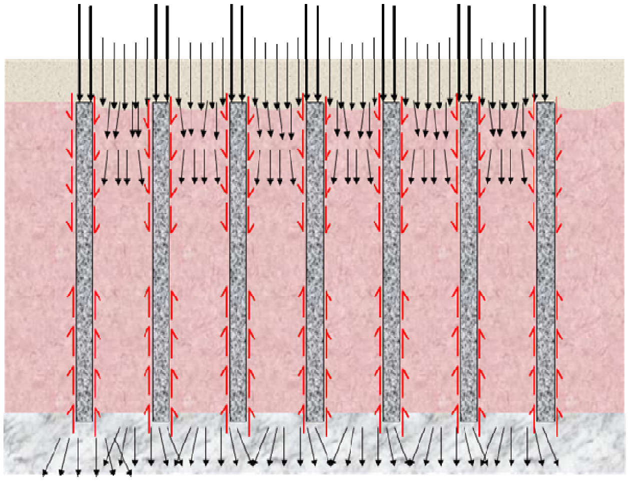


FIGURE 3 Load distribution between soil and an inclusion network.

While calculation methods have been proposed by various authors (see Combarieu), with the development of more powerful computers, finite element method (FEM) analysis has quickly become the method of choice when designing a network of CMCs.

CMCs FOR STORAGE TANKS

CMCs have been used to support numerous bulk liquid and solid storage tanks around the world. Some of the factors why CMCs are so commonly used for support of storage tanks include:

- Many refineries, terminals and industrial facilities are located in coastal areas or along waterways where very soft alluvial soils are present;
- Storage tanks with denser product or greater product heights may exert extremely high bearing pressures that renders ground improvement solutions using deformable inclusions inadequate due to excessive settlement or bearing capacity failure;

- Because of the very deep zone of influence of large storage tanks, in areas it is necessary to extend the CMCs to depths of 100 feet or deeper. Achieving such depths with many other forms of ground improvement is typically not practical;
- The heavily reinforced concrete pile cap required if piles are used is not necessary;
- Many tanks are constructed where contaminated ground is present. Only a negligible amount of spoils are generated. These materials are readily worked into the platform and disposal/management is not required; and,
- Because CMCs are sealed by virtue of the grouting process and self cased drilling, aquacludes are not breached and potential migration paths for contaminated groundwater or leaked product are not introduced.

CMCs are typically installed 1 to 3 feet below the tank bottom. A compacted granular LTP is installed above the top of the CMCs and below the tank after installation of the CMCs. The main purpose of the LTP is to transfer the load from the tank to the CMCs without the use of pile caps between the tank bottom and the CMCs. The load is transferred to the CMCs through arching within the high phi-angle LTP and through side friction below the top of the CMCs. Because the CMCs are totally isolated from the structure, utilities, vapor barriers, cathodic protection systems, and liners can be easily installed directly under the tank bottom within the LTP.

CMCs are usually installed beneath the centerline of the concrete ringwall that supports the tank shell. The CMCs typically terminate 6 to 12 inches below the bottom of the wall. The spacing of the elements below the ringwall is governed by the ability of the surrounding soils to share the load with the CMC elements while maintaining deformations within acceptable tolerances. The LTP is typically extended beneath the ringwall and occupies the zone between the top of the CMC columns and the ringwall. In effect, the LTP may be thought of as a cushion that separates the tank and ringwall bottom from the top of the CMCs.

CMCs may be designed to accommodate moderate uplift conditions by placing a centralized bar in the elements and extending the bar into the ringwall as required. This is sometimes required where tanks are situated in flood prone areas.

CASE HISTORY - PETROLEUM STORAGE TANK, PORT OF QUEBEC CITY, QUEBEC

This project involved the improvement of the foundation soils for five petroleum product tanks at a facility in the Port of Quebec City. The 120 foot diameter tanks were planned to be built on a structural slab supported by a network of pressure injected footing type piles.

To reduce construction costs, a ground improvement solution using CMCs was proposed. The requirement for the ground improvement was to achieve a net bearing capacity of 5 kips/sf. The computed post-construction differential settlement was required to be less than 1 inch, which corresponds to an angular deflection of 1:730.

Geotechnical Conditions

Stratigraphy over the site of the five tanks was typically composed of a loose surficial fill of silty sand varying to sandy silt about 16 feet thick, covering a layer of wood and organic waste material with lenses of silt and sand. The total thickness of the organic layer varied between 5 and 8 feet. Natural dense sand with some silt was present underneath this soft compressible layer. The exact total thickness of this natural soil was not indicated in the geotechnical study but was expected to be about 100 feet, based on available geological information. At the time of the geotechnical investigation, groundwater was present at a depth of about 10 feet. The ground water level is tidally influenced and at certain times of the year, the groundwater level was just below the ground surface.

Design of CMC System

Settlements and stresses in the CMCs were computed using the FEM software Plaxis and an axisymmetrical model of the unit cell composed of the CMC and its surrounding soils. Soils and CMC properties used in the computations are summarized in Table 1.

TABLE 1 Characteristics of the Soil Layers Used in the FEM Analysis

Material	Thickness (ft)	Young's modulus (psf)
Upper sandy fill	16	375,900
Organic silt	8	62,660
Lower dense sand	±100	626,600
Load transfer platform	2	1,044,000
CMC	26	365,500,000

Computation results are summarized in Table 2 below.

TABLE 2 Results of FEM Analysis for the Unit Cell

Grid spacing (ft x ft)	Column diameter (inches)	Settle-ment (inches)	Column stress (psi)
5 x 5	12	3.4	750

Modeling Of Tank Using Equivalent Soil Modulus

In order to estimate the differential settlement due to the tank geometry itself, an axisymmetrical model of the whole tank and the improved soil was used. The modulus of the improved composite soils used in the calculations is an equivalent modulus computed from the results of the axisymetrical unit column model.

The equivalent Young's modulus of the composite soil is based on the computed settlement and the stress (σ) applied on top of the CMCs per the following elastic relationship:

$$\frac{\Delta H}{H} = \frac{\sigma}{E_{equivalent}}$$

Where ΔH is the settlement and H is the total thickness of the composite layer, CMC and the load transfer platform. Based on the calculated results for the unit cell model, the equivalent modulus of the reinforced soil mass was estimated at 584,800 psf. The load applied by the tank was 5,000 psf. All other soil parameters were kept similar to the previous model.

The axisymmetrical calculation results are shown graphically on Figure 4. Based on this model, the settlement at the center of the tank was expected to be approximately 3.15 inches, and the settlement under the ring wall was about 2 inches with a differential settlement between the center and the edge of approximately 1.1 inch as shown on Figure 4.

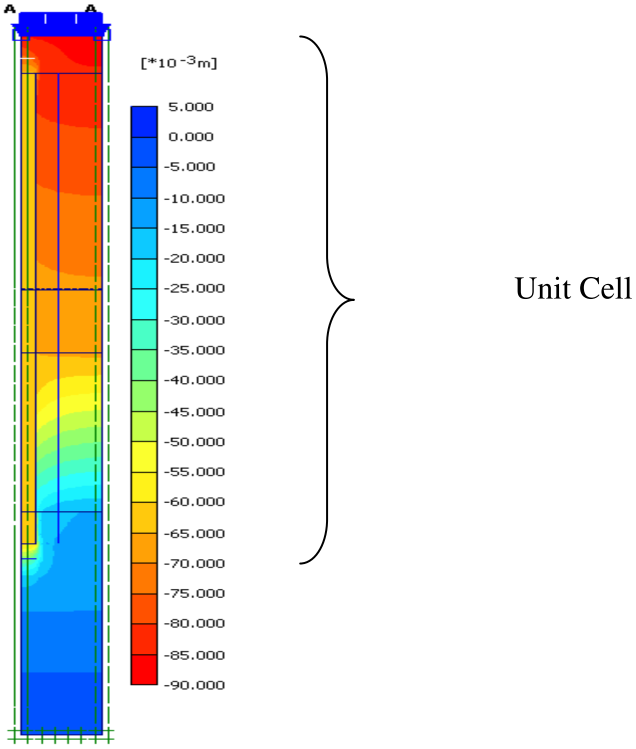


FIGURE 4 FEM settlement computation results for the unit cell.

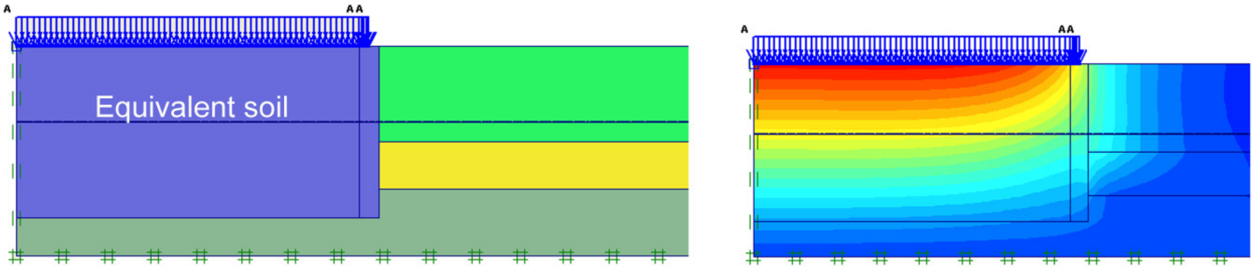


FIGURE 5 Model and results of FEM computations of the soils under the tank load.

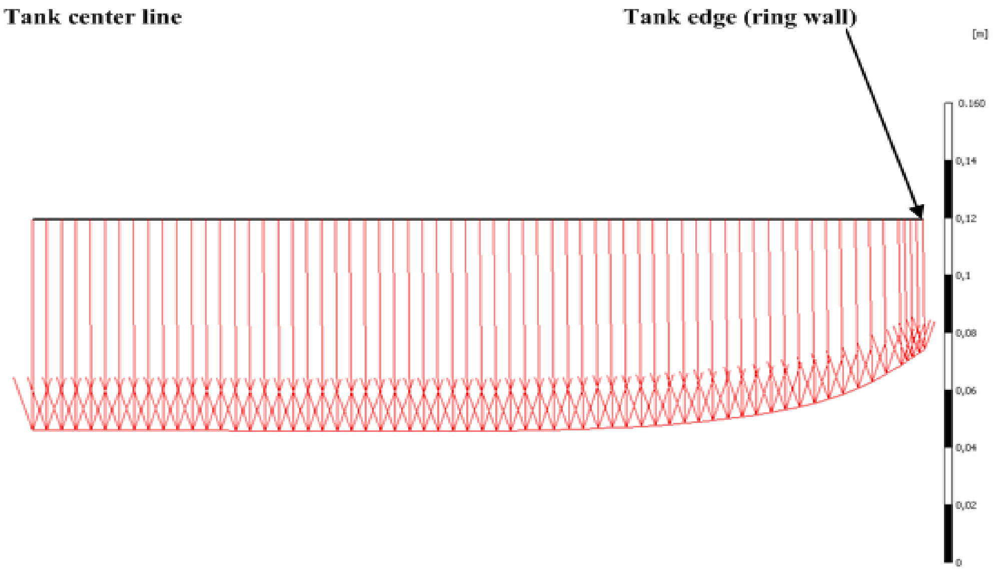


FIGURE 6 Predicted settlements under the tank load.

The calculated differential settlement results are on the conservative side since the previous model did not take into consideration the following factors:

- the depth of embedment of the tank
- the increased rigidity of the outer edge (ring wall) of the tank

On this basis, it was considered that the differential settlement between the ring wall and the center of the tank would be less than 1 inch.

Construction and Measured Settlements

During the tank hydro-test water test, settlements varying between 1 and 1.4 inches were measured along the periphery of the tanks. These values, smaller than those computed, can be explained by the use of conservative material properties and by the fact that the effect of soil densification between the inclusions was ignored in the models. Nevertheless, it shows that relatively accurate settlement estimations, with a conservative safety margin, can be obtained with the methods describe herein.

FIGURE 7 Installation of the CMCs in Quebec City.

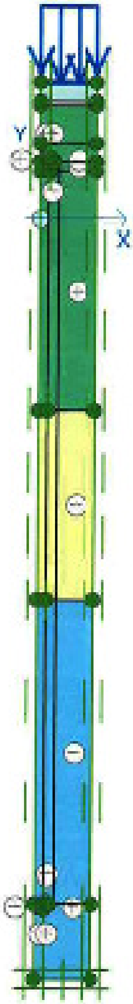
CASE HISTORY – TEXAS CITY, TX

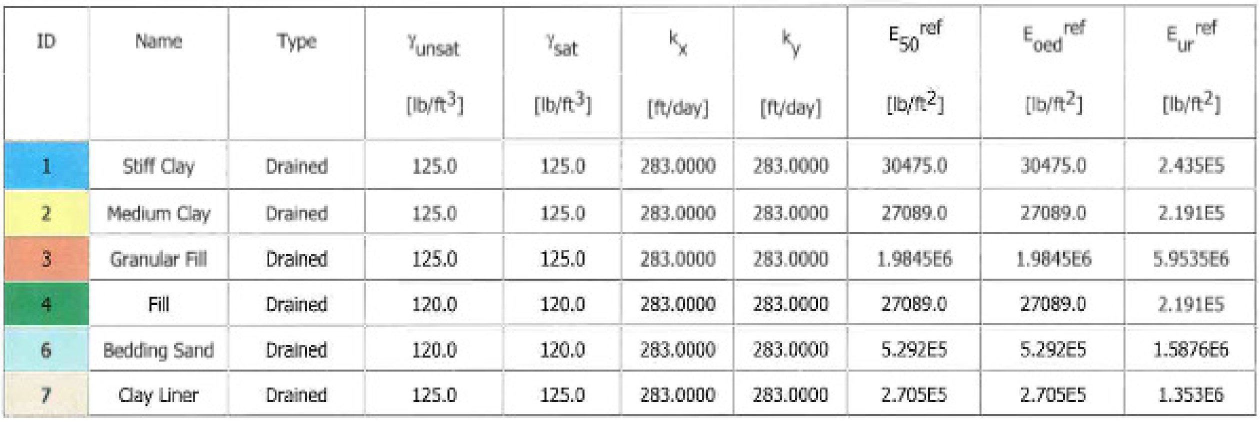
In Texas City, Texas CMCs were used to support a total of seven new tanks at an existing oil refinery tank farm. One tank was 62 feet in diameter, four of the tanks were 115 feet in diameter, and two tanks were 150 feet in diameter. The product heights for the tanks were 56 feet. In addition to supporting the storage tanks, CMCs were also used to support earthen ramps which were constructed to allow access into the tank area, which was encircled by reinforced concrete containment walls. The ramps were constructed to provide a convenient and safe access for equipment and vehicles to enter the storage tank area.

The site is underlain by a layer of clayey fill that varies in thickness across the site. Below this layer lies a soft to medium stiff clay, which increases in stiffness extending to a depth of 40 feet. A layer of stiff to hard clay is present below the softer clay layer. Without ground improvement, significant settlement would have occurred for both the tanks and the access ramps.

Design of the CMC System

The design was performed using a 2D axisymetrical model in Plaxis. The settlement of the deeper layers below the tip of the CMCs was evaluated using classical consolidation theory by hand. To estimate the total long term settlement of the system, both settlement estimations were added together.





ID	Name	Type	γ_{unsat} [lb/ft^3]	γ_{sat} [lb/ft^3]	k_x [ft/day]	k_y [ft/day]	E_{50}^{ref} [lb/ft^2]	E_{oed}^{ref} [lb/ft^2]	E_{ur}^{ref} [lb/ft^2]
1	Stiff Clay	Drained	125.0	125.0	283.0000	283.0000	30475.0	30475.0	2.435E5
2	Medium Clay	Drained	125.0	125.0	283.0000	283.0000	27089.0	27089.0	2.191E5
3	Granular Fill	Drained	125.0	125.0	283.0000	283.0000	1.9845E6	1.9845E6	5.9535E6
4	Fill	Drained	120.0	120.0	283.0000	283.0000	27089.0	27089.0	2.191E5
6	Bedding Sand	Drained	120.0	120.0	283.0000	283.0000	5.292E5	5.292E5	1.5876E6
7	Clay Liner	Drained	125.0	125.0	283.0000	283.0000	2.705E5	2.705E5	1.353E6

FIGURE 8 Model properties – Axisymmetrical Model.

The model is shown above. A soil-Hardening behavior law was selected for all layers except the CMC itself which was defined an elasto-plastic material.

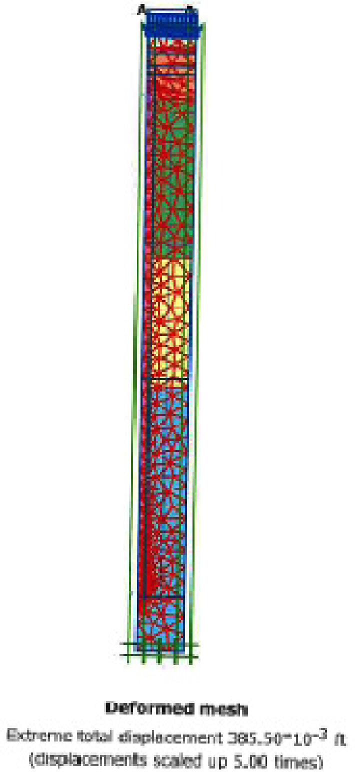


FIGURE 9 Deformed mesh plaxis.

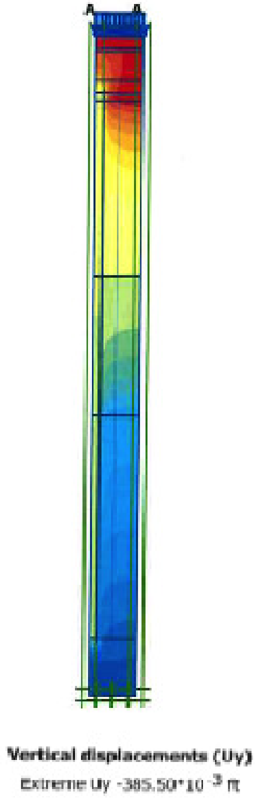


FIGURE 10 Vertical displacement plaxis.

The calculated settlements are summarized below in Table 3. Two types of analysis (best and worst case) were performed. Estimated total settlements ranged from 7.8 inches to 10.3 inches.

TABLE 3 Estimated Settlements in Best and Worst Case

	Settlement, inches	
Zone of Settlement	Least	Greatest
Within CMC – Reinforced Zone	Directly Above CMC	Between CMC's
	4.500	4.632
Below CMC – Reinforced Zone	Edge of Tank	Center of Tank
	3.29	5.69
Total	Minimum	Maximum
	7.79	10.32
Differential	2.53	

Two single element load tests were installed in order to verify the assumptions of the design. Based on the results of the FEM analysis, the design load was 115 kips. At design load, the movement of the CMCs was under a quarter of an inch which was well within the design parameters.

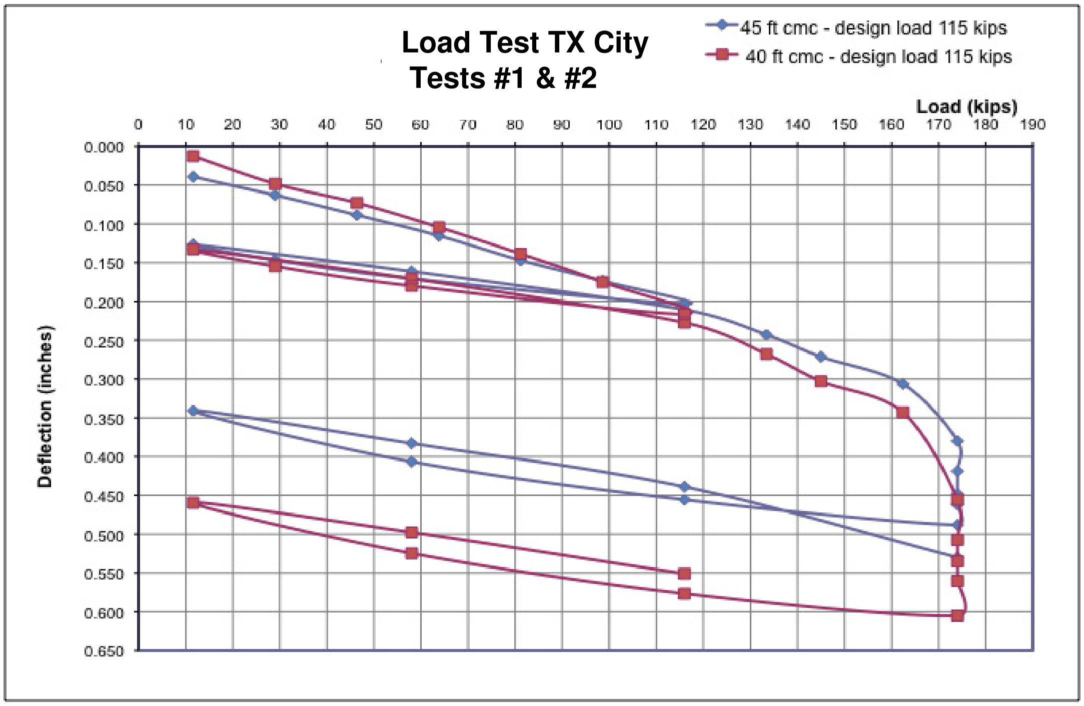


FIGURE 11 Plot of two load tests performed on a 40 ft and a 45 ft CMC.

The CMC ground improvement solution consisted of the installation of a total of 1,800 CMCs, to maximum depths of 45 feet. Over 77,000 lf of CMCs, 12.5-inches in diameter were installed.

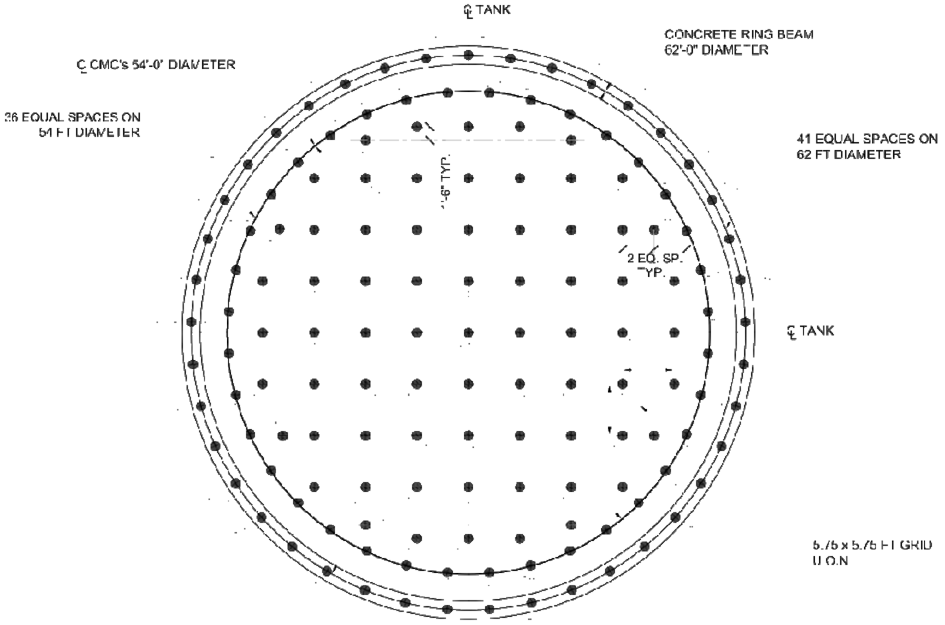


FIGURE 12 Typical layout under 62 ft diameter tank.

FIGURE 13 Texas City CMC installation site.

CONCLUSION

CMC technology spans a wide range of economical solutions for heavily loaded structures when piling or other deep foundations are the initial means for gaining support. By eliminating heavy structural mats and pile caps, while at the same time allowing the compatible sharing of support with the soil, results in the optimal use of all materials. Since the elements do not drain, long term consolidation is discouraged, and undesirable vertical transport of groundwater contaminants is not promoted. Spoil generation is nil, eliminating the costly disposal of contaminated ground. Performance is more predictable and subject to less variation, since real time monitoring allows for adjustment of column depth as the site is traversed and the bearing conditions vary. Speed of construction is enhanced since traditional steps (like surcharging and concrete construction) are eliminated.

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