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Support of MSE Walls and Embankments Using CMC

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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 mixes can be placed from the bottom up once the hole is founded at 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 behind the development and experience with CMC makes them uniquely efficient for the immediate support of MSE walls and embankments for public transportation, other infrastructure facilities, large storage tanks, and building facilities.

Traditional embankment and fill wall construction for road and rail corridors had placed little value on time in developing the engineering schemes for settlement control prior to placing pavement. As an improvement to the least first cost alternative – waiting for primary consolidation to occur - when working above fine-grained soils prone to long term consolidation, wick drains with surcharge have been commonly applied to speed up the settlement process. This approach can still take up to 1 year depending on site conditions, wick drain spacing, thickness of the slow-draining layer, and the degree of consolidation desired prior to paving. Accelerated construction of embankments, with immediate placement of roadway pavements over compacted embankment fills offers a very desirable solution.

CMCs are an ideal solution for the immediate support of embankments. 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.

CMCs are designed using special proprietary finite element techniques that include the effects of load sharing between the distribution platform, the columns, and the surrounding improved ground. Special considerations for bearing into the distribution layer are made, as well as detailed designs for reinforcement of the distribution layer if required to control differential settlements.

The paper summarizes the design approach, and presents case histories of completed public facilities supported on CMC foundations. The case of an MSE bridge approach in New Jersey is discussed in detail and the support of a deep arch culvert in Pennsylvania is briefly presented.

1 INTRODUCTION

It has long been established that Mechanically Stabilized Earth (MSE) Structures tolerate significant total and differential settlements. The excellent performance of the early Reinforced Earth ® walls and abutments constructed in the 1970's and 1980s's that underwent large settlements instilled confidence in engineers and owners, and led to widespread use of MSE walls as the retaining wall type of choice when building on soft soils. The experience gained on the early structures with large total and differential settlement led to specifications and guidance based on facing panel tolerance to differential settlement. However, there is minimal AASHTO, FHWA or state DOT guidance with respect to total allowable settlements of MSE walls.

Three basic construction methods may be considered for MSE walls constructed on soft soils; Single Stage, Phased, and Two-Stage. Depending on foundation conditions and construction schedule requirements, any of the three construction methods may be used in combination with ground improvement methods such as Controlled Modulus Columns (CMC™). In addition to primary settlements which occur during the construction of an MSE wall, the tolerance to post construction foundation settlements of the pavement, utilities and other structures built atop MSE walls need to be considered in determining the need for foundation improvements. Conventional single stage construction, or multi stage, where at specific elevations, time elapses to allow primary consolidation to happen before raising to the final height, is used when total and differential settlements are tolerable.

Where waiting time is not available, ground improvement measures may be considered to readily allow construction of a conventional single stage MSE wall. As a last alternative which is often more time consuming and costly than a solution on ground improvement, a two-stage wall may be considered when primary settlements are not compatible with the intended facing system, and where single stage methods are precluded by prevailing site and/or time limitations. The general principle behind a two-stage wall system is to first construct a flexible wire-faced MSE wall, allowing large scale settlements to occur, then attaching precast panels to the first stage reinforcements or constructing a cast-in-place face.

Depending on the foundation conditions, the overall schedule of the project as well as economical considerations, it may be beneficial or necessary to improve the foundation materials prior to construction of the MSE wall. Support of MSE structures with a ground improvement solution is economical for both cost and shortened time of construction. The use of Controlled Modulus Columns™ (CMC) is an ideal solution for the support of MSE Walls, steepened slopes and conventional embankments. The authors have experience with value engineering projects that were initially designed for 2-stage construction, into single stage walls on CMC ground improvement.

Often, owners of bridges are not comfortable allowing larger settlements for approach walls, wing walls, and abutments. Piles or drilled shafts supporting conventional reinforced concrete abutment walls, are still used extensively. When deep foundations are specified, it is generally where compressible soils exist below the structure. In some cases, the reinforced concrete walls are replaced with Reinforced Earth Walls, and piles are retained under short (stub) abutments and extended through the reinforced earth structure. This is called a "false abutment". Where the settlements of the Reinforced Earth structure are not tolerable, ground improvement is used to support the structure as well. When the investment is made in ground improvement, it makes more sense to the authors to consider construction of a "true abutment", where the Reinforced Earth wall transmits the load of a stub on spread footings to the wall directly. The foundation support for the RE wall then needs to be designed for smaller movements to retain proper performance of the bridge. Significant economies are possible with expanded application of this approach.

Vertical inclusions such as Controlled Modulus Columns ™ (CMC), have been used successfully for the support of MSE walls over soft soils (Masse, et. al 2008). The principle of these inclusions is to reinforce the weak foundation soils with vertical inclusions of compacted granular material or grout. These inclusions carry most of the load of the MSE Wall to competent layers at depth reducing considerably the amount of settlement induced in the compressible layers by the weight of the embankment.

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.

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 MSE wall or embankment and the ground shears or ruptures, causing a rotation of the Wall and/or embankment or punching of the wall 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 serviceability of the road above the embankment or wall, with a very high risk of rupture and significant loss in term of road closure and repair works. Failures occur when the weight of the embankment 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.

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 bearing capacity and circular failure.

2 CONTROLLED MODULUS COLUMNS

2.1 *Description of the Technique*

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 embankments, they require the use of a structural mat, relieving platform or pile cap to connect the tops of the piles together to provide a foundation for the embankment. The structural mats, relieving platforms or pile caps 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 therefore eliminating the need for a rigid connection between elements.

Controlled Modulus Column^{TM} (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 or MSE wall, 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 ft below the bottoms of the MSE structure or embankment. 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 / embankment / MSE Wall 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.

2.2 *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. 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.

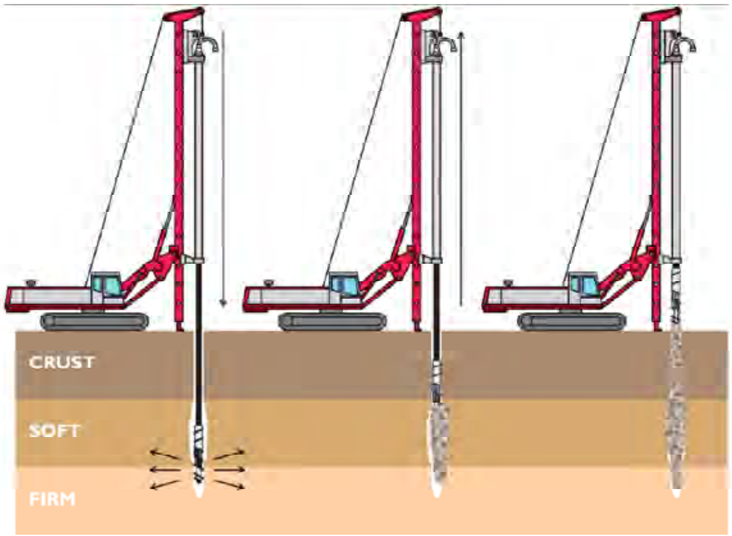


FIGURE 1 CMC installation schematic.

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 nonexistent, except in a case of 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.

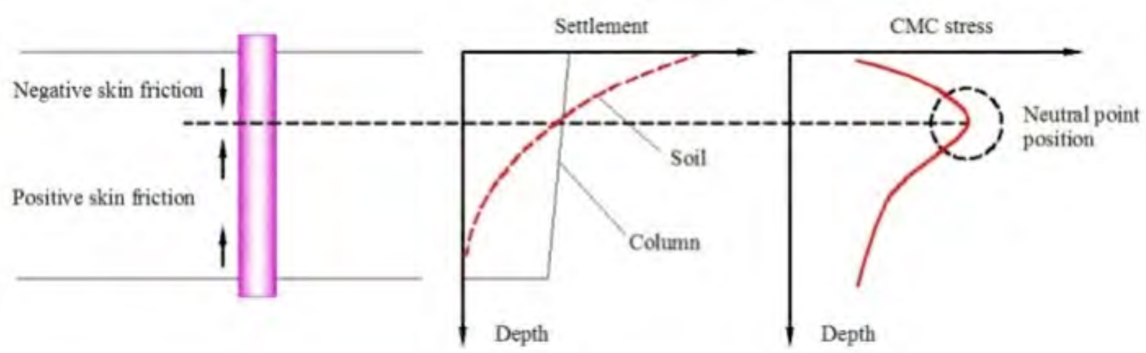
A significant benefit of the recordation of installation parameters is that changes in subsurface conditions can be detected in the field, and more importantly, column depths can be adjusted based on the encountered conditions as detected by the response of the drilling equipment. The recorded drilling 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.

2.3 *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



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.

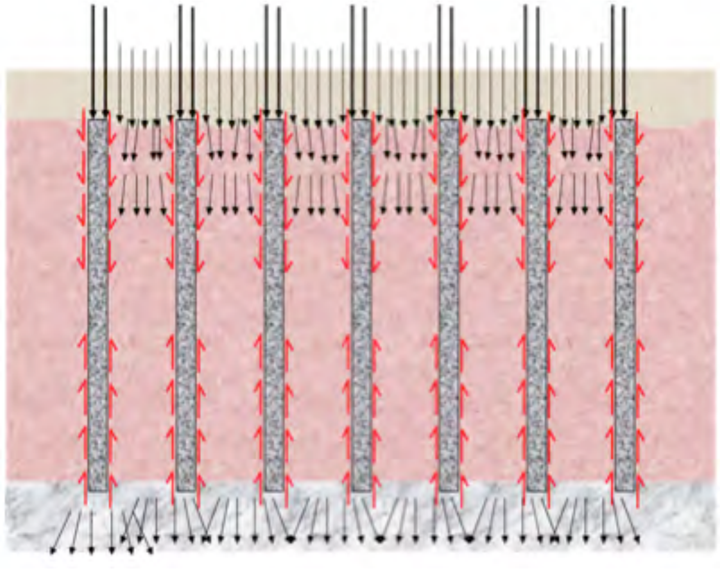


FIGURE 3 Load distribution between soil and an inclusion network.

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.

3 CASE STUDY : SINGLE STAGE MSE WALL WITH CMC SUPPORT IN NEW JERSEY

3.1 *Single Stage MSE Wall with CMC Support in New Jersey*

This Interchange between two major highways in Northern New Jersey is a $149 million rehabilitation and reconstruction project undertaken to complete the links between the road systems, and improve traffic flow and safety for local communities by allowing a more rapid access to the highways.

This project involved the construction of two new ramps, a bridge approach and a new underpass to allow access to the highways from local communities. The project specified several sections of Mechanically Stabilized Earth (MSE) retaining walls, and embankments supported by ground improvement. For this project owned and operated by the New Jersey Department of Transportation - NJDOT, ground improvement using CMCs was proposed to help support the bridge approach embankments.

The site is underlain with silt to clay and silt to fine sand with gravel – highly variable fill over bedrock. The fill thickness ranged from five to twenty feet in depth. The average depth to bedrock ranged from 15-35 feet. The fine to coarse sand fill layer included debris consisting of brick, concrete fragments, cinders, wood, metal, and glass.

CMCs were proposed as a value-engineering alternate to Vibro concrete columns. To support the embankments and MSE wall sections, over 400 CMCs were installed for a total of 8,460 linear feet of grouted column. The maximum depth required for the CMCs was 35 feet.
Although several ground improvement options were considered for the project, CMCs were selected as the most appropriate solution for the job based on the construction schedule, total settlement and overall cost.

Figure 4 – CMC installation under the MSE Wall

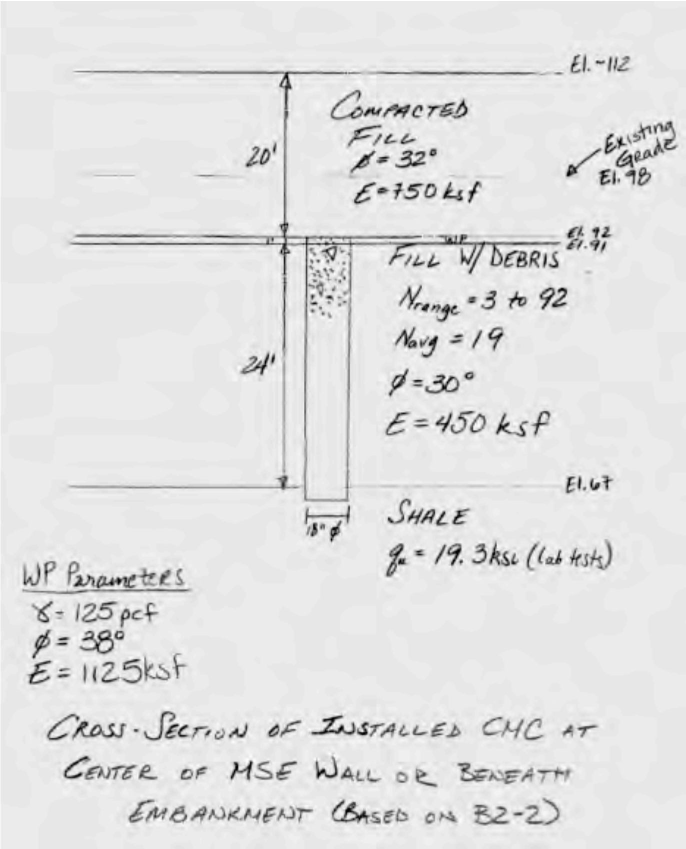


Figure 5 – typical profile under the MSE Walls and Embankments

Settlement and Stresses were computed using the FEM Software package Plaxis and a combination of 2D-Plain strain as well as axisymetrical modeling techniques in order to represent different proposed loading conditions. Overall, it was found that there was good agreement between the two types of models regarding the predicted settlements and the expected load sharing ratios between CMCs and the surrounding soils.

The axisymetrical model was performed using an 18 inch CMC and represented a typical unit cell located beneath the proposed embankment toward the center of the MSE Wall. The wall height used for this model was 21 ft above the top of the CMCs. The CMCs were extended 1ft into the lower shale with a modeled length of around 25 ft. A plane strain model was also performed for the same profile and section of roadway representing 4 CMCs installed beneath the proposed embankment, MSE wall and roadway. The results of the plain strain model predict the settlement that will occur during construction of the embankment and MSE Wall and the distribution of load between soil and CMC. This type of modeling also allows us to evaluate the global stability of the embankment and MSE wall supported by CMCs and to provide a global factor of safety against failure through a C-phi reduction analysis. Because a 3D configuration is modeled using a 2D plane strain simplification, the CMCs are modeled as infinite walls that extend infinitely perpendicular to the model plane. Because of this limitation, the stiffness and surface area of the modeled elements need to be adjusted to represent an actual stiffness and surface area of the discrete CMC elements. The results of the 2D plain strain models are shown in the following figures.

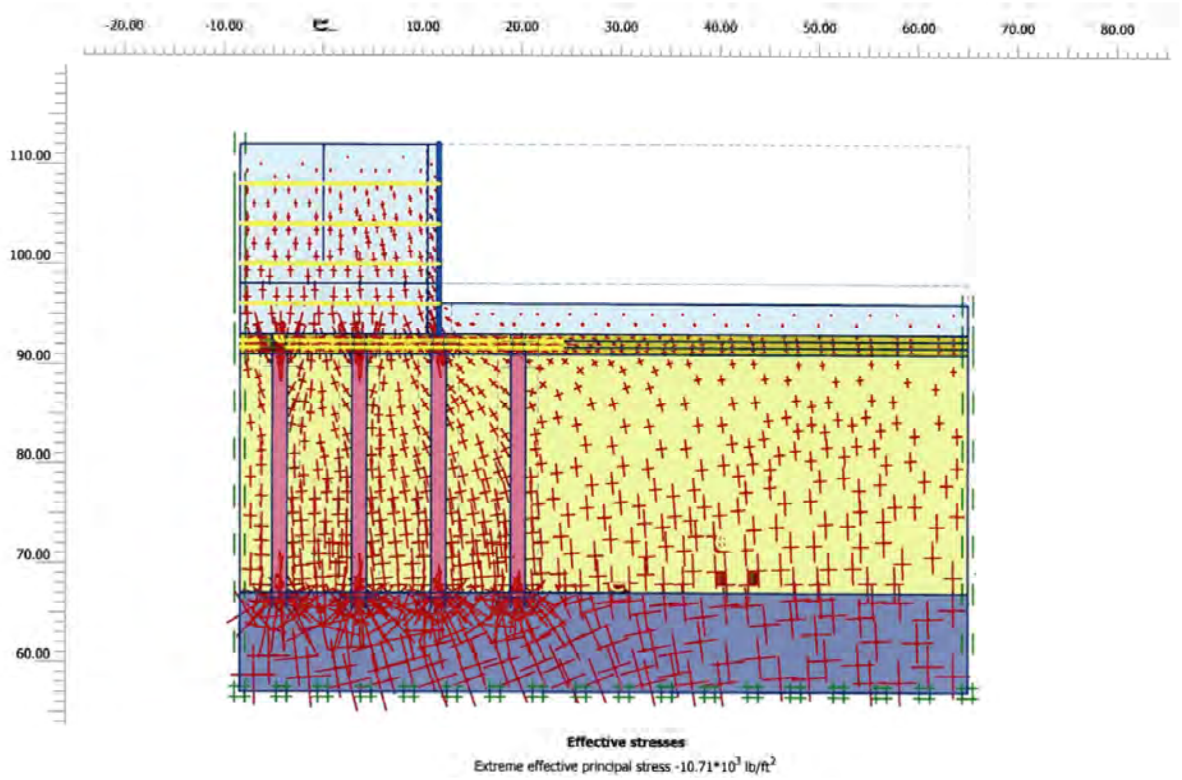


FIGURE 6 stress distribution under the MSE Wall in 2D plane strain model.

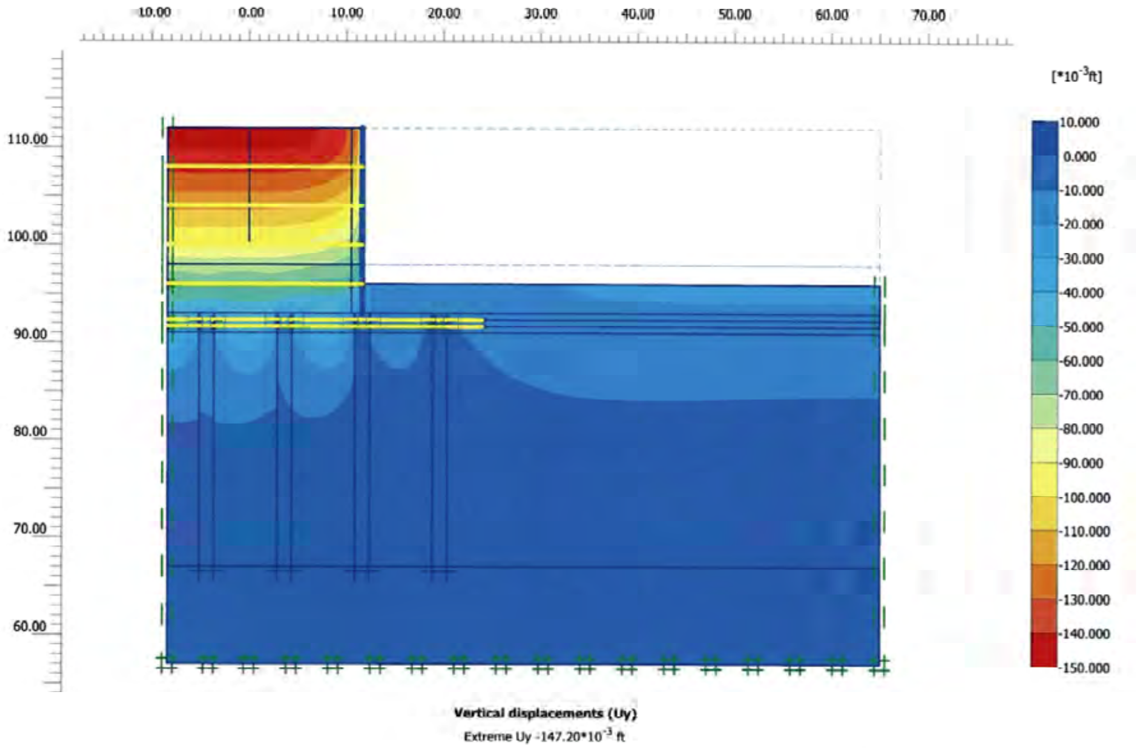


FIGURE 7 settlement profile under the MSE Wall in 2D plane strain model.

The results of the axisymetrical model showed a total settlement of 1.6 inches at the top of the MSE Wall with a tip movement of the CMCs limited to 0.1 inch. The plane strain model resulted in a total settlement of 1.8 inches at the top of the MSE wall with a similar CMC tip movement. Both models showed that approximately 60% of the applied load was carried by the CMCs and 40% by the surrounding soils, which is comparable to other sites with similar conditions.

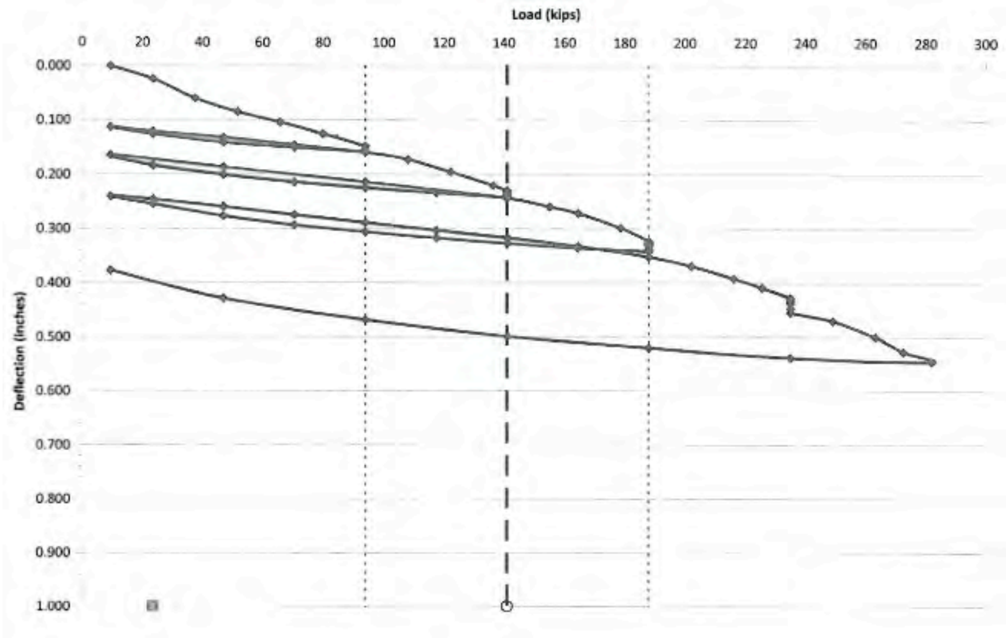


FIGURE 8 Single Element Modulus Test

Two single element modulus tests were performed on two different CMCs to verify the geotechnical capacity of the CMCs. The maximum load applied on the 18 inch elements during the test was 280 Kips. The MSE Wall was constructed using the Reinforced Earth Company Wall System. The MSE Wall was instrumented and movements were recorded for a period of several months. The settlement data showed a maximum movement of around 1 inch after the monitoring period as shown below.

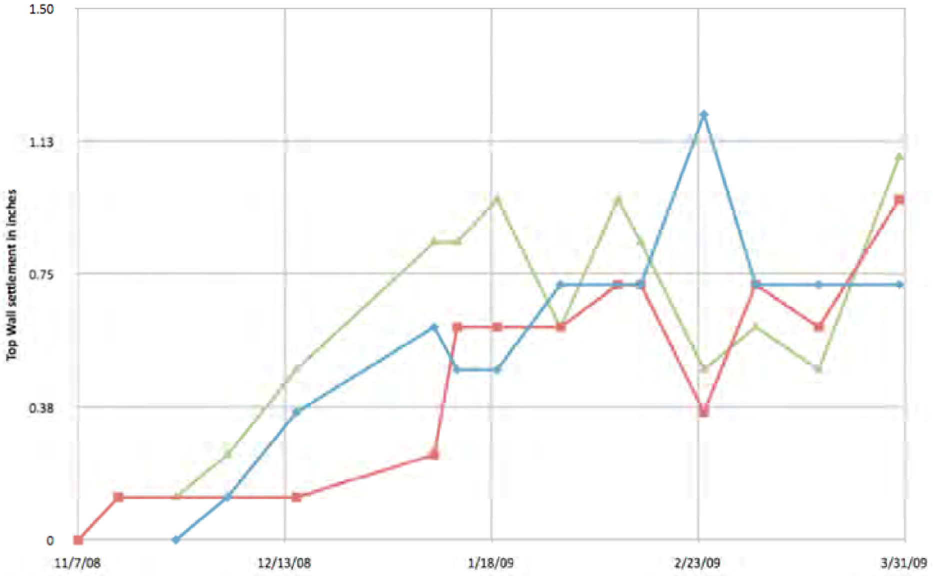


FIGURE 9 CMC-supported MSE Wall monitoring results

FIGURE 10 view of the MSE Wall under construction

3.2 *Deep Arch Culvert supported on CMCs in Western Pennsylvania*

This project involved the replacement of a small culvert on a county road and the realignment of the roadway at an intersection. The new culvert was constructed in a new location to improve safety and mobility at the realigned intersection. The new road goes over an existing stream and the existing culvert was replaced by a deep precast arch culvert. The new road sits atop the culvert with embankments up to 30 to 35 ft high sloping down each side of the culvert. The bid proposal from the PA DOT had a generic performance spec for ground improvement under the culvert foundation. Loads were given, and the design-build ground improvement contractor was also made responsible for final detailing of the mat slab.

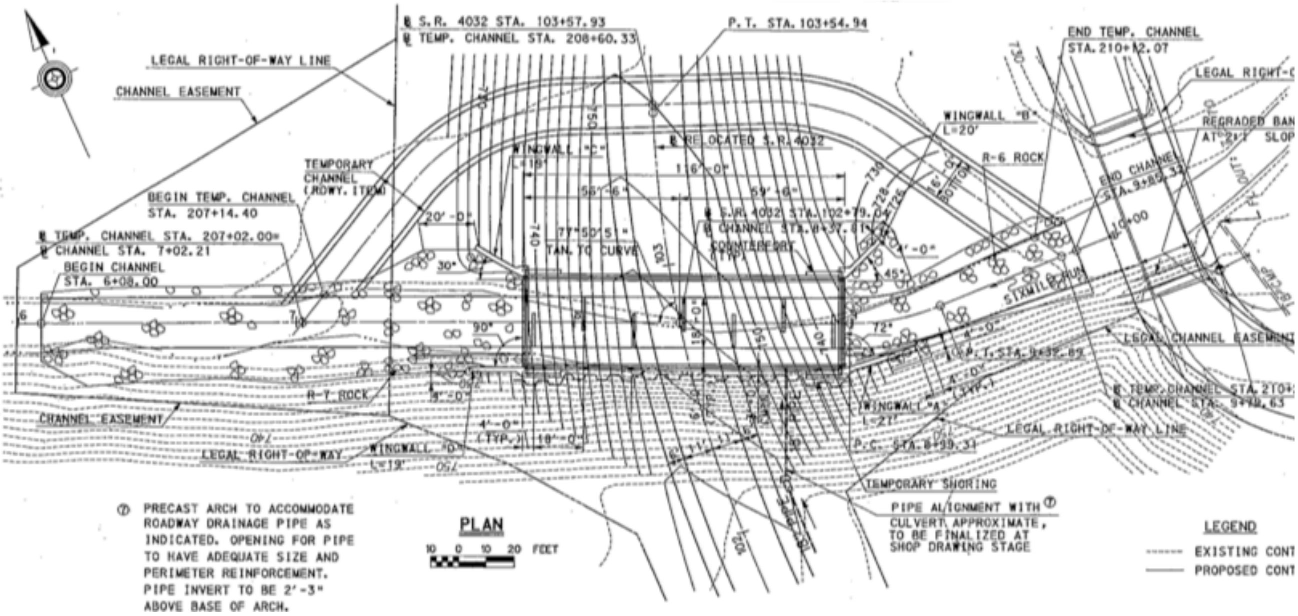


FIGURE 11 general plan and elevation of the new roadway and arch culvert

The soil investigation showed the presence of successive layers of silty sands with lower N-SPT values in the upper 30ft. A system of around 160 Controlled Modulus Column (CMC) was designed to reinforce the upper soft soils and limit the total and differential settlement of the proposed arch culvert and the embankment above it. The CMCs were also installed to provide adequate bearing resistance to support the culvert. This job was let as a design-build open-ended specification that gave the contractor opportunities to propose the most technically and economically attractive solution to the project team.

The design was based on the results of a 2D-plane strain model performed for a profile that was agreed to be the worst case scenario in terms of fill / load being placed over the culvert. The soil boring with the softest soil conditions was used to determine the geotechnical cross-section.

The plane strain model depicted half of the foundation since the General Contractor was proposing laying back the side where permanent shoring was specified in the original plan making a similar profile on both sides.

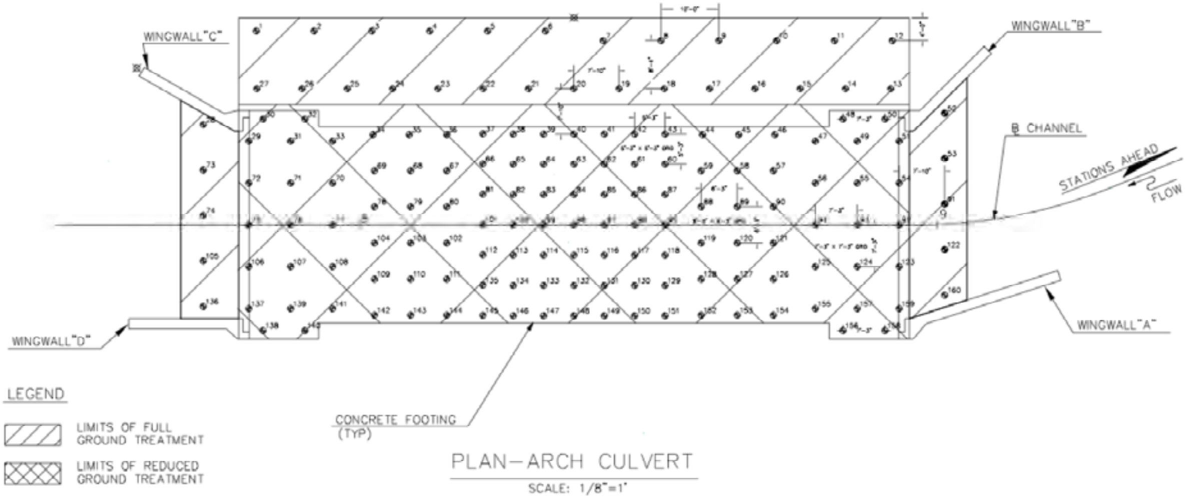


FIGURE 12 : General Layout of the CMC columns

Two single element load tests were performed to verify the load capacity of the 12.5 inch CMCs and validate the movements predicted by the models. Thanks to the use of the CMC system, the project was able to go ahead and be completed within the schedule and budget set forth during the budget phase.

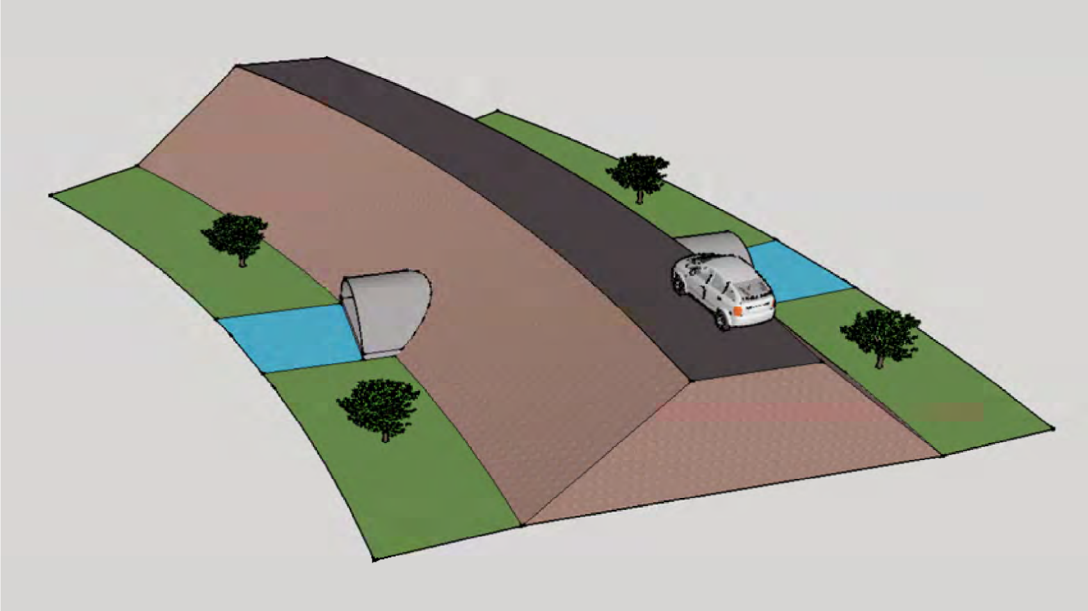


FIGURE 13: Conceptual view of the project

4 CONCLUSION

CMC technology spans a wide range of economical alternative solutions for heavily loaded structures, high MSE Walls, embankments, and bridge abutments when piling or other deep foundations are the initially envisioned 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 by using a Load Transfer Platform, it 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 for MSE Wall and embankment since traditional steps (like surcharging with or without use of wick drains or 2-stage MSE Walls) are eliminated.

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