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Support of MSE walls and reinforced embankments using ground improvement

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ABSTRACT: Surcharge in combination with wick drains in highly compressible soils have traditionally been used to economically reduce post-construction settlements and construction time. Surcharging a wall structure or steep reinforced slope is more complicated given deep seated global stability concerns. 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. CMC are pressure grouted auger displacement columns installed with a specially designed tool at the working end of a high torque, high down pressure drilling machine. To address sliding forces from retaining walls, high tensile geogrids are incorporated into a distribution layer and additional analyses are performed to check the lateral bending in the CMC elements. This paper summarizes the design approach and highlights two corresponding case histories.

1 CONTROLLED MODULUS COLUMNS

1.1 *Overview*

Controlled Modulus Columns (CMC) were developed first in Europe to meet technical, financial and quality requirements of a constantly more demanding ground improvement market. They are vertical semi-rigid inclusions designed to obtain a composite material (soil + inclusions) with controlled stiffness and they represent one of the best ground improvement technologies to date in terms of speed of construction, quality-control, reliability, range of applications and cost.

CMCs belong to the same class of ground improvement systems as the stone columns or the more recent vibro-concrete columns in the sense that they improve at the macroscopic level the overall stiffness of the foundation soils. More precisely, CMCs are filling the gap between the so-called rigid deep foundations (RDF such as piles, caissons and drilled shafts) and the more deformable foundation systems (DFS such as stone columns, rammed aggregate piers and dynamic replacement pillars). For RDF, the load of the structure is completely transmitted to the elements through a direct connection with the structure (pile caps or thick mats). For DFS, the modulus of deformation of these elements is compatible with the surrounding soils, creating a load sharing combination that results in a more deformable system with the structure supported on a load transfer platform usually made of densely compacted granular material. The CMC technology somewhat reconciles these two approaches by bringing together the advantages of both technologies into one hybrid solution, which offers better stiffness and better settlement reduction than the DFS without the difficulties and cost of a structural connection with the structure normally associated with RDF.

1.2 *Means and methods for the installation of CMCs*

The CMC technology has the following characteristics:

- A displacement hollow-stem auger is used to drill the inclusions. The auger has three main components: the bottom part penetrates into the ground and evacuates the cuttings upward – the middle part displaces the ground laterally by pushing the cutting to the sides – the upper part, with its flights in the reverse direction from the bottom part prevents any spoil or grout to reach the surface.
- In order to penetrate most ground, a high torque – high pull down drill rig is necessary.

In constructing CMC, the auger is first introduced into the ground and is advanced using the high torque and pull down available on the rig. No grout is inserted

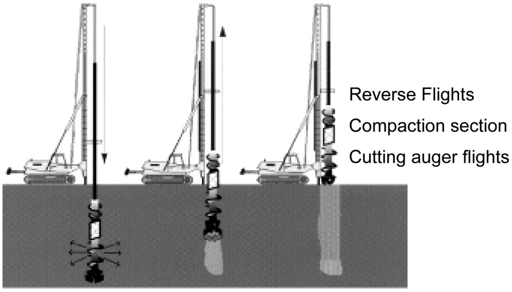

Figure 1. Installation of a controlled modulus column (CMC).

at this stage. When the required depth is reached, the grout is pumped through the hollow stem of the auger with sufficient pressure to overcome the gravity and lateral pressures at the tip of the auger. The auger is then extracted while turning in the same direction as during the drilling phase in order to avoid loss of grout and spoil migration along the shaft of the hole and along the kelly bar thanks to the reverse flights of the upper part of the displacement auger. (figure 1)

This results in virtually no spoil at the surface and no vibration during the whole process. The use of CMC is highly recommended for sites with constraints such as vibration limitations or for projects located on contaminated grounds as it eliminates the need for disposal of spoils.

Each inclusion is monitored by an on-board instrumentation device that can record the following parameters:

- Drilling phase: speed of penetration, torque, pull-down, depth, speed of rotation of the auger
- Grouting phase: pressure of grout, volume of grout, speed of rotation and extraction

The integration of these parameters by the on-board computer allows the visualization in real-time of the actual profile of each column. All the parameters can be recorded for later reporting.

2 USE OF CMC FOR SUPPORT OF MSE WALLS AND REINFORCED SLOPE EMBANKMENTS

When designing a CMC solution for support of an embankment (MSE Wall or reinforced slope), several factors have to be taken into account:

- Bearing capacity requirements
- Final elevation of the road as compared to the initial existing grade (loads)
- Width of influence of the embankment (i.e. depth of influence of new stresses)
- Risks of slope failure (i.e. global stability)
- Analysis and design of the load transfer mechanism
- Lateral spreading and lateral displacement of the elements.

CMCs are designed using numerical modeling techniques that include the effects of load sharing from the wall or the slope to the distribution layer, the columns and the surrounding improved soils. In particular, it is critical to understand the behavior at the interface MSE Wall/Load Transfer Platform (LTP)/CMC in order to accurately model the load transfer mechanism and to avoid large differential settlement of the CMC into this layer.

Design calculations are usually performed using PLAXIS or an equivalent software package and leads to the selection of the spacing of the CMCs. Depending upon the amount of tolerable construction settlement, i.e., sufficient strain to engage the tensile strength of a geogrid, the necessity of reinforcement by geogrid in the transfer layer can be selected. The evaluation also gives the stresses in the ground and in the column resulting from the stress distribution model. It is thus possible to refine the design parameters (diameter of the columns, grid of installation, thickness of the transfer layer and compression strength of the grout) to optimize the total cost of the solution. Once the design parameters have been chosen at the discrete level of a single column, a global elasto-plastic calculation can be performed using the same numerical modeling program to take into account specific boundary conditions such as:

- variable height of fill along the same section or non-symmetric loading conditions
- horizontal loads due to train braking friction on tracks for a railway embankment
- rapidly varying thickness of compressible ground along a given section
- variable CMC grid of installation

This second calculation usually allows the confirmation of compliance with the deformation criteria for the structure and allowable stresses inside the columns. Because 2D elements are usually used for the calculations, it is necessary to replace the layer of CMC + surrounding soil(s) by a global uniform layer defined by equivalent characteristics.

3 CASE STUDY #1: (1H:4V) MSE WALL IN KINGSTON, JAMAICA

The project consisted of the construction of a new section of a Tollway located on the coastal shores between Portmore and Kingston, Jamaica. The 7 km section goes through a mangrove swamp underlain by an organic peat layer and very soft clay layers up to 22 m deep. The road was generally set about 2 to 3 m above the existing ground elevation and wick drains

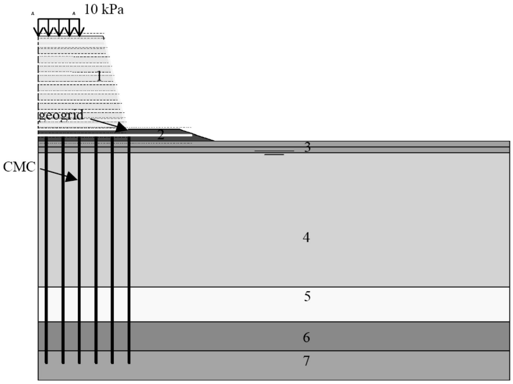

Figure 2. Typical numerical model – MSE embankment (1H: 4V) and CMCs – not scaled.

Figure 3. Site works in Jamaica – View of the bridge abutment area.

and surcharge were designed to accelerate the consolidation of the compressible layers. Nevertheless, three major interchanges, overpasses and a toll plaza were also to be built and the schedule did not permit the use of a classical solution for the consolidation of these compressible layers. The approach embankment to these overpass bridges reached up to 10 m on some portions of the highway. A CMC-supported embankment solution was designed for these sections of the job. A standard unreinforced embankment using 2H:1V or 3H:1V slopes was not feasible without creating additional costly and time-consuming requirements for land purchase. A solution using a steep (1H:4V) geosynthetic-reinforced embankment with a wire-faced MSE approach supported by CMC was designed for the project (Figure 2).

The project overall specification was to limit the residual settlement after the opening of the road to 200 mm over the next 35 years and to ensure a long term factor of safety against slope failure above 1.3. To deal with long term secondary consolidation of the soft compressible layers and to accommodate the differential settlement between the bridge on piles and the approach abutments, two resurfacing programs were priced into the overall cost of the maintenance of the highway by the contractor.

Figure 4. Wire-faced MSE Wall – 1H:4V Wall.

The construction sequence was selected based on the results of the evaluation. As shown below, the stress ratio used for the soft layer was around 98%, which showed limited long term settlement due to the load of the MSE wall. It was therefore decided that no surcharge or construction of the wall in steps was necessary to meet the long term settlement requirements of the project.

The results of the 2D numerical analysis are summarized below:

Case	MSE wall
Embankment height	9 m
CMC length	19.5 m
Geogrid reinforcement	1 layer
Stress in the geogrid layers	79.1 kN/m
Geogrid deformation	3.9%
Settlement under static load from embankment	184.5 mm
Settlement under live loading from traffic	20 mm
CMC Load	400 kN
Stress distribution ratio	98%

4 CASE STUDY #2: REINFORCED EARTH EMBANKMENT – MIAMI, FLORIDA

4.1 *Description of the project*

This project involved the creation of an auxiliary ramp along the existing SR836 operated by the Miami-Dade Expressway Authority in Miami, Florida. Due to extremely constrained site conditions, the contract documents called for a design-built solution using a column-supported MSE wall for the abutments to the bridge. The wall height ranged from 4 m to a maximum of 10 m at the bridge connection with bearing pressures including overturning of up to 0.25 MPa. Part of the road extension was located under the existing slopes of the current road, while the rest was located beyond the existing slope, creating a risk of differential settlement as well as increased risk of slope failure. Also, part of the existing slope was "demucked" prior to construction to replace soft organic layers with crushed limestone material and sand, while the outer part of the wall was seated on highly compressible organic peat.

4.2 *Technical requirements/specifications*

Because of the presence of existing buildings along the alignment of the new lane, the settlement criteria were extremely strict for this project. The design-build specifications allowed "a maximum 1.3 cm deflection of the reinforced platform at the middle distance between two" inclusions. They also stipulate that the ground improvement system should be designed so as to "produce negligible settlements to adjacent structures and to avoid punch-through of the Load Transfer Platform". The total length of the project was 140 m for Wall 1A and 300 m for wall 3A, with reinforcing strip lengths varying from 3 to 8 m.

4.3 *Subsurface conditions/typical soil profile*

The available geotechnical information for the project was somewhat limited with less than 10 standard penetration test values obtained along the alignment of the wall outside the actual footprint of the wall. These borings showed heterogeneous conditions along the axis of the proposed lanes. The boring that indicated the poorest subsurface conditions was located at the bridge abutment where the wall was at its maximum height. The typical cross section was as follows:

- Upper 1 m, dense crust consisting of cemented sands, limerock fill with silts
- Below this crust, a 3 to 4.5 m thick layer of silt and organic silts (ML to CL-ML) with varying sand and clay contents, very soft to stiff depending on the location
- The bearing layer was comprised of a silty to clean sand (SP to SM) underlain by limestone.

4.4 *Design using numerical analysis*

In order to fully account for the pressure due to the MSE wall, it was necessary to incorporate in the calculations the effect of the moment created by the active forces acting at the back of the wall volume. The direct effect of this overturning moment was to create an eccentricity "e" in the line of application of the gravity load of the wall and the traffic load. As a result, the bearing pressure increased at the toe and decreased at the heel of the wall. The Meyerhof method was used to compute these pressures, whereby the weight of the wall and the traffic load were assumed to be applied on a reduced width of B-2e (B is the strip length and e is the eccentricity). The overturning effect increased the bearing pressure under the wall by as much as 0.85 ksf at the maximum height of the wall.

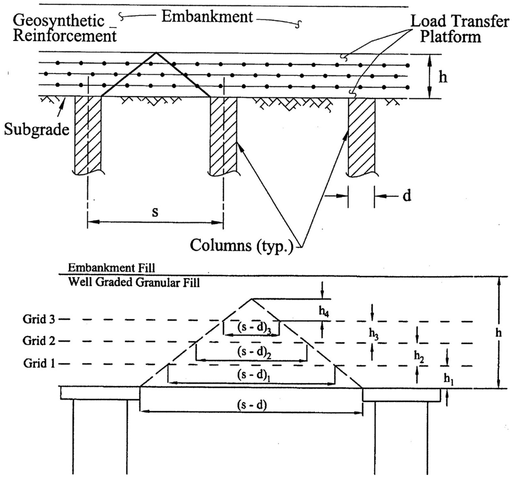

Figure 5. Load transfer platform design concept.

4.4.1 *Design of the Load Transfer Platform (LTP)*

Based on the project requirements, an extensive design of the LTP was performed across the project. The design was based on the Collin method (figure 5). This method is based on the premises that the reinforcement (minimum of three layers of geogrid) creates a stiffened beam of reinforced soil that will distribute the load of the embankment or MSE wall above the LTP to the inclusions below the LTP. The primary function of the reinforcement in that case is to provide lateral confinement of the fill in the LTP to facilitate arching within the thickness of the LTP. The reinforcement supported the wedge of platform below the arch in order to avoid settlement in-between the inclusions.

The vertical load carried by each layer of reinforcement is a function of the column spacing and the vertical spacing of the reinforcement. Each layer of geogrid is designed to carry the load of the LTP within the soil wedge below the arch. As a result, the vertical load on any layer (n) of reinforcement (Wtn) can be determined from the equation below:

Wtn = [area of geogrid layer n + area of geogrid layer n + 1]/2 × layer thickness × LTP density/area of geogrid layer n.

The tensile load in the geogrid is then determined based on tension membrane theory and is a function of the strain in the reinforcement.

4.4.2 *Numerical analysis*

A series of Plaxis calculations were performed for different loading cases as well as different soil profiles.

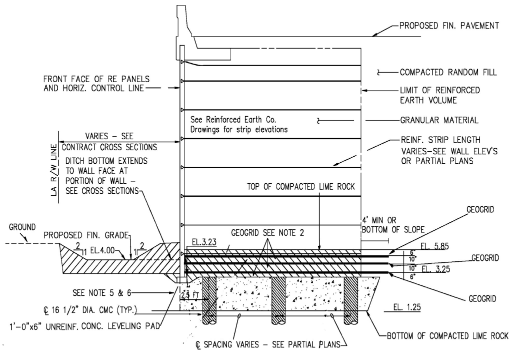

Figure 6. Typical cross-section of final design.

On wall 1A, an analysis was performed for a 6 m, 8 m and a 10 m high wall section with grids of installation of respectively 2.05 m, 1.83 m and 1.52 m (center-to-center on a square pattern). On Wall 3A (figure 6), an 8 m high wall and a 10 m high wall were analyzed. Long term settlement of the system ranged between 0.4 to 0.6 cm; well within the tolerance of the specifications.

A total of more than 950 CMCs were installed to support the two MSE walls.

4.5 *Site work pictures*

Figures 7 and 8. View of CMC rig and MSE Wall during construction.

5 CONCLUDING REMARKS

The Controlled Modulus Columns (CMC) foundation is one technique of ground improvement for support of industrial or residential structures as well as embankments (unreinforced and reinforced slopes) and MSE walls. The design methodology and case histories presented herein demonstrate the effectiveness of the CMC foundation system in terms of settlement performance and speed of construction. When used with a properly designed Load Transfer Platform, it provides suitable and economical support for MSE walls over compressible subsurface conditions.

CMC technology does not generate spoils and does not bring contaminated soils to the surface. In a challenging world where development of marginal sites is a necessity for the survival of future generations, this technology offers a competitive sustainable alternative to classical deep foundations.

REFERENCES

Collin, J.G. & al (2004) – FHWA – NHI Ground improvement manual – Technical summary #10: Columns supported embankment – FHWA – 2004

Dumas, C. & al (2003) Innovative technology for accelerated construction of bridge and embankment foundations in Europe – FHWA-PL-03-014, FHWA 2003

Masse, F. & al. (2004) CMC: potential application to Canadian soils with a new trend in ground improvement – CGS 2004, Winnipeg, Canada

Plomteux, C. & al (2003) – "Reinforcement of Soft Soils by Means of Controlled Modulus Columns" – Soil and Rock America 2003, pp 1687–1694

Plomteux, C. & al (2003) – "Controlled Modulus Columns (CMC): Foundation system for Embankment support: a case history" – Geosupport 2004, Orlando, USA, pp 980–992

Porbaha, A. & al (2007) – "Design and monitoring of an embankment on controlled modulus columns" – TRB paper #06-1743 – Transportation Research Board, 2007

Plaxis finite element code for soil and rock analysis – user's manual – Plaxis V8 – 2007