Execution & Engineering Principles of Control Modulus Column (CMC)

K.Coghlan, C. Plomteux & J. Racinais
Menard SAS, Nozay, France

ABSTRACT: CMC is a soil improvement technique consisting of a mortar semi rigid column which was first developed by Menard-France in the mid-nineties. The concept was initially conceived as an alternative to stone columns. The development of this new technology resulted in Menard carrying out the first CMC project in 1996 in the north of France. The CMC foundation system is now used across Europe, North America, Asia and Australia. CMCs are effective in all soil types, but particularly in soft cohesive clayey or silty soils in order to prevent excessive or adverse settlements, but also provide stability and adequate structural bearing capacity. It is based on a load sharing system between the soil and the column. It is commonly used beneath structures with uniformly distributed loads such as warehouses, caisson quaywalls, embankments, wind turbines and storage tanks. This paper will provide basic execution and design principles of the CMC.

1 HISTORY OF CMC TECHNIQUE

1.1 *Brief History*

The concept of deep foundation systems or reinforcing underlying soils has existed for many centuries. Examples can be found across the globe, detailing wooden piling systems in 15th century Venice, Italy to the use of oak trees in the 16th century to consolidate soils beneath the chateau of Chambord, Loire in France.

For a modern structure requiring a deep foundation system due to the presence of soft soils, there are various types of soil reinforcement techniques available. Not unlike the science of geotechnics, the idea of soil reinforcement is still a relatively new concept which has developed through various innovative techniques since the early nineteen sixties. Soil reinforcement techniques as a concept, make use of what capacity is within the soil and compensate as necessary using stiffer materials to achieve the required bearing capacity or settlement reduction. This is in contrast to piling which transfers the full structural load to a deeper substrata, and effectively replaces any founding capacity in surface layers.

The invention of techniques such as Dynamic Compaction in 1969 by Louis Menard, Hamidi, Nikraz & Varaksin, (2009), allowed geotechnical engineers to improve in-situ soil parameters of loose granular soils rather than installing traditional piled solutions.

The CMC is an unreinforced concrete column which was initially developed to fill the gap between potentially more expensive pile solution and classical soil improvement techniques such as vertical drains or stone columns. The combination of very soft soils and a more stringent settlement criteria, would have traditionally ruled out the use of soil reinforcement, therefore requiring a more expensive piling solution. Like all soil reinforcement techniques, the principle of ‘controlled modulus column’ is not necessarily to stop settlement but to control it to within acceptable limits.

The CMC technique was first developed and executed in 1996 for the Amien Football Stadium project in Amien, in the north of France.

Today, CMC is a widely accepted Rigid Inclusion technique within the geotechnical industry and has been executed in various regions around the world since 1996.

Recommendations for the design and execution of CMCs, now exist within the first ever guideline for soil reinforcement techniques, ASIRI (2013) ground improvement guideline.

2 CONSTRUCTION OF CMC

Execution of CMC can be implemented using a variety of techniques including soil extraction or soil displacement methods.

2.1 *Bored CMC with Soil Extraction*

2.1.1 *Simple Bored*

The process of simply bored CMCs is carried out in soils which are self-supporting and generally this means cohesive soils..

2.1.2 *Continuous Flight Auger Method (CFA)*

The CFA method employs the use of a hollow flighted auger similar to that used for standard piling methods. The principle is the same as that of CFA in that concrete/mortar is injected under pressure as the tool is raised up to platform level. One particular example of this technique is the Nigh Son Petrochemical Project in Vietnam. The project comprised of 32 no steel tanks varying in diameter from 25m to 70m. CMCs were designed up to 20m in depth in soft to stiff clays with sand lenses. The specification required consisted of differential settlement - tank center to edge < R/300; Circumferential Settlement – 13mm per 10m; Tilt Settlement < Dia/200

2.1.3 *Bored CMC with Displacement Auger Method*

The CMC displacement method requires a rig of high hydraulic capacity and specifically designed auger with reverse pitch to laterally displace material. Concrete is then pumped through the hollow stem of the auger under pressure as the auger is raised from the required depth to the working platform level. This technique ensures minimal spoil over the platform.

2.1.4 *Cast In Situ Vibro Concrete Column (VCC)*

This execution method consists of lowering a tube with a valve or clamp at the lower end, into the soil to the required depth. The vibrated void is then filled with concrete. Penetration is either carried out using vibrator at the end of the tube or a hydraulic or diesel powered vibrator attached to the top of the tube.

2.2 *Load Transfer Platform*

It is required to place a load transfer platform (LTP) over the CMCs in order to uniformly diffuse the load amongst the inclusions. This ensures that the CMC/soil combination acts as a composite layer. The LTP can consist of various different materials.

2.2.1 *Granular Mattress*

The most common type of LTP is a layer of granular material compacted layer by layer. This generally is a well graded sand or gravel with less than 10% fines with a thickness ranging between 0.4 and 0.8m in thickness however this depends on the conditions on site and the geometry of the foundation.

Figure 1. Vibro Concrete Column

2.2.2 *Geotextile Reinforcement*

Should the required thickness of LTP not be possible, a single or numerous geotextile membranes can also be incorporated into the platform.

2.2.3 *Steel Reinforcement*

Where calculation shows that horizontal or lateral loads are beyond the capacity of a CMC section, a steel reinforcement mesh can be incorporated into the transfer platform. A typical example of this is beneath high embankments (>8m on very soft soils) where lateral loads can become large. This was used successfully on the LGV High Speed Train project from Paris to Bordeaux as seen below in figure 2.

Figure 2. Steel Reinforcement Cage under Embankment – LGV Project Paris - Bordeaux

2.2.4 *CMC Cap*

Where CMCs are installed in very soft soils to support an embankment height of 2.5m or less, this may be susceptible to an undulating effect on the platform. The load for such a small embankment is generally quite low, resulting in a wide grid of CMCs. This type of arrangement can be susceptible to settlement between columns. To counter this effect, a system of caps can be constructed on the head of the CMCs. The dimensioning of the CMC and the Caps should satisfy the condition in equation 1, ASIRI (2103) and figure 3 below:

$$H_M > 1.5(s-a), \tag{1}$$

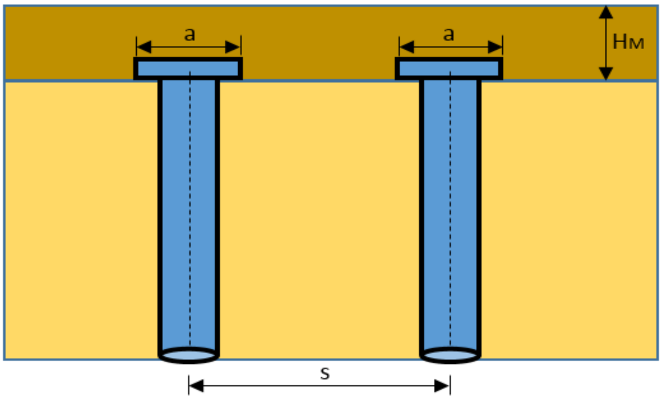

Figure 3. CMC Cap with Minimum LTP

3 DESIGN OF CMC

Generally CMCs are designed to achieve specifications such as minimum total settlement, minimum differential settlement, bearing capacity; minimum factor of safety for stability.

3.1 *Principles of Settlement – Deformation Analysis*

The analysis of deformation of composite soils reinforced with CMCs can be divided into a number of steps.

Step 1: Application steps of load at surface level. This will in turn induce a deformation within the CMC, δ_{cmc} and within the surrounding soil, δ_{soil}.

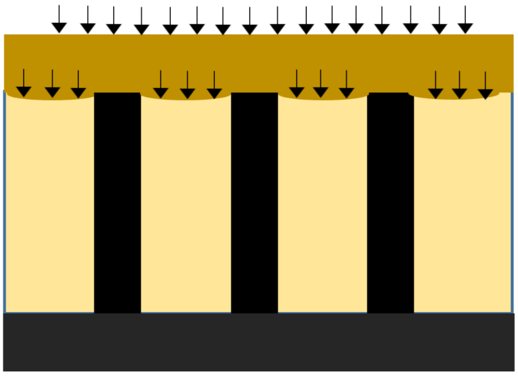

Figure 4. Step 1 – Application of Load at Surface with Deformation of Soil between CMCs

Step 2: The deformation within the soil is greater than the deformation within the CMC, $\delta_{soil} > \delta_{cmc}$. This will cause negative skin friction along the surface of the CMC above the neutral axis (NA). Therefore, this subsequently transfers the stress from the surrounding soil to the CMC.

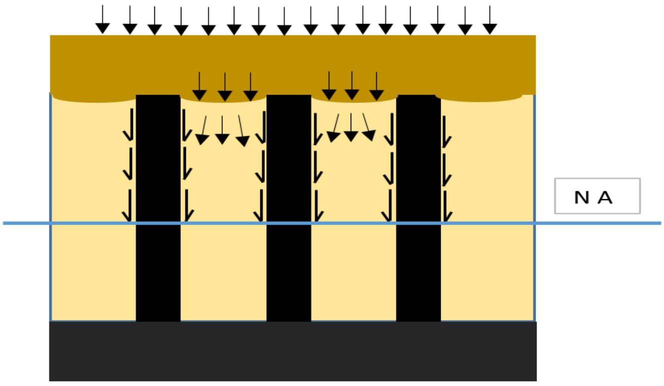

Figure 5. Step 2 – Induced Negative Skin, above the Neutral Axis (NA) along CMC due to Deformation of Soil

Step 3: At the Neutral Axis, $\delta_{soil} = \delta_{cmc}$ therefore this is point of maximum stress in the CMC. Below the neutral axis, $\delta_{cmc} > \delta_{soil}$ creating a mobilisation of positive skin friction and end bearing resistance.

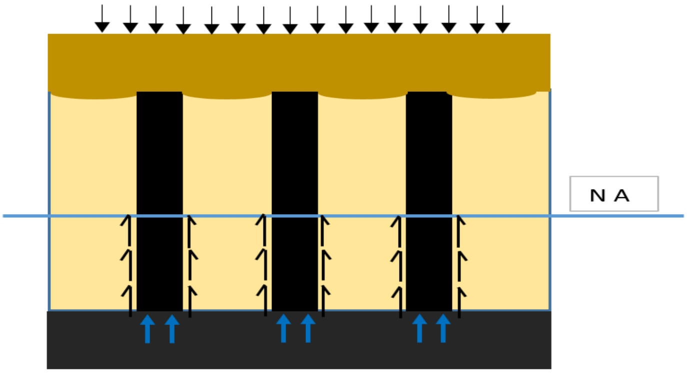

Figure 6. Step 3 – Mobilisation of Positive Skin Friction and End Bearing Resistance below Neutral Axis (NA)

Step 4: Finally once sufficient capacity within the founding layer has been mobilised, a state of stress equilibrium is reached.

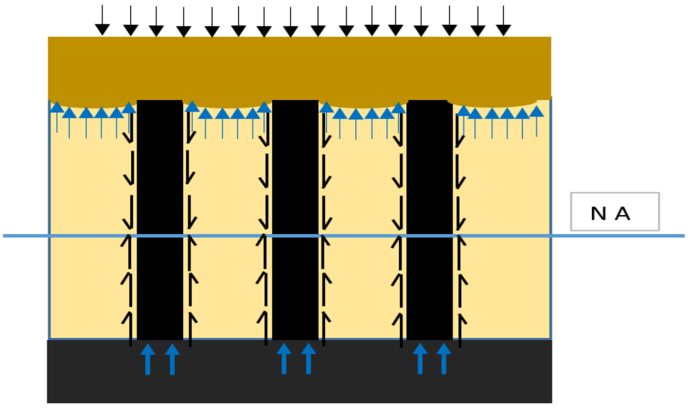

Figure 7. Step 4 - State of Equilibrium

In order to understand the localised stress distribution between the CMC and the natural soil, generally an analysis is carried out using FEM software in two steps.

Localised axi symmetric model is performed considering the grid, column diameter, length of CMC column, characteristics of concrete/mortar etc to understand the skin friction and end bearing interaction.

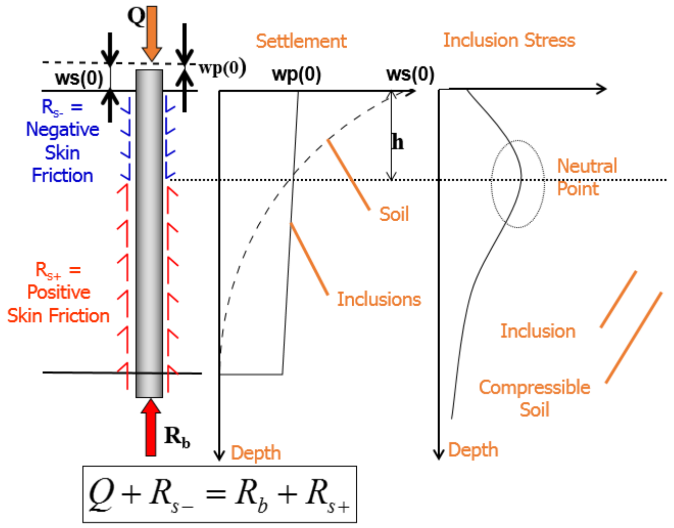

Figure 8. Example of Stress Distribution in CMC/Soil Interface

Once localised parameters have been calculated and validated, these are then used to compile a global model incorporating all external factors

3.2 *Global Bearing Capacity*

As a primary check, and as the CMC concept is reliant on a load sharing system between column and soil, based on basic CMC design of grid and column diameter, it is required to verify the following formula 2, ASIRI, (2013):

$$q_{ref} .S \le q_{soil}.(S - A_{cmc}) / \gamma_{soil} + S . q_{cmc} / \gamma_{cmc} \qquad (2)$$

where q_{ref} = average stress of structure on the soil; q_{soil} = average stress over area of the soil; q_{cmc} = average stress over area of the CMC Column; A_{cmc} = Area of CMC Column; S = Area of influence for one CMC

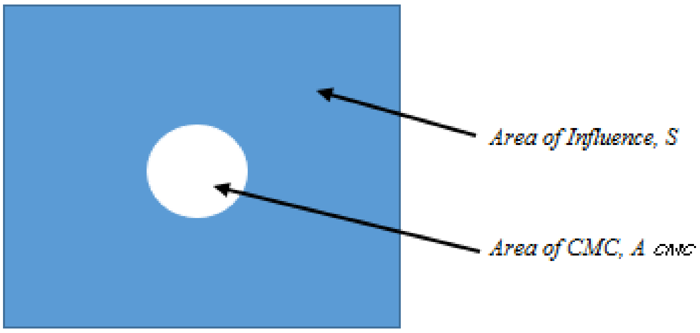

Figure 9. Area of Influence of CMC

3.3 *Design Checks*

3.3.1 *Allowable Stress at CMC Head*

It is required to verify that the maximum allowable stress value at the head of the inclusion is compatible with the LTP characteristics (material and geometry).

Using equations of the failure mechanism (Prandtl's diagram), of the load equilibrium and of the load bearing capacities of the soil and the inclusion material, it is possible to determine the allowable domain of the limit stress in the LTP at the inclusion head.

In figure 10, q_s+ and q_p+ are the stresses applied on the supporting soil and at the inclusion head respectively. The allowable domain is reduced to the intersection of the segment (4) with the shaded surface.

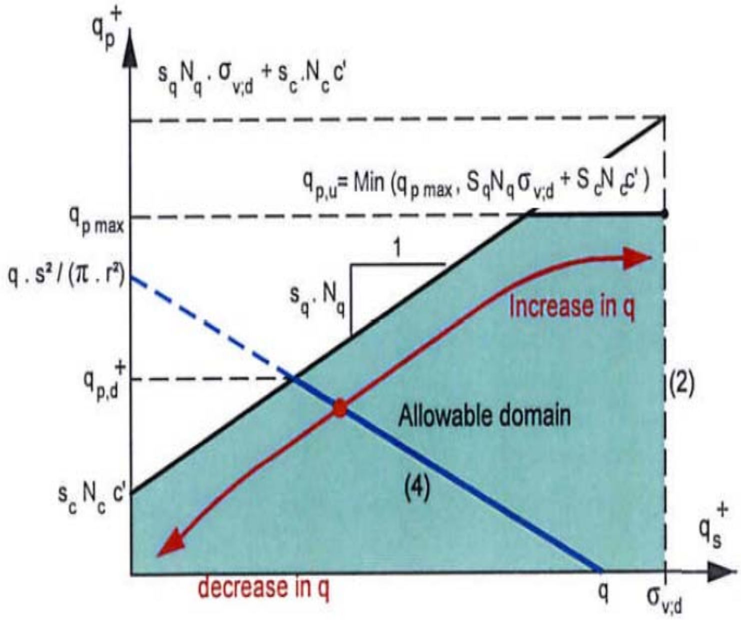

Figure 10. Stress Interaction between CMC & Soil, ASIRI (2013)

4 ENGINEERING APPLICATIONS

The following provides some previous applications of CMC and how the technique has been used in order to achieve the specification required for each structural application.

4.1 *Tanks*

Tank structures concentrate a high load over a relatively small surface area. The critical criteria for any steel or concrete tank being the control of differential settlement.

One recent example of tanks founded on a CMC system, is the Marrero Magellan Project in Louisiana, USA. The project was carried out in 2014 and detailed five no 40m dia tanks with reinforcement of soft silty clays to 25-32m with column diameters ranging from 320mm and 420mm. An innovative ring beam using reinforced earth was also implemented as a part of this project in order to reduce differential settlements between the edge and the centre of the tank.

4.2 *Embankments*

As previously mentioned, CMC is an effective system as a foundation solution to control total and differential settlements as well as providing slope stability against shear failure below embankments.

The ideal load case for this technique is where the CMC is almost fully in compression, however due to the inclined nature of an embankment, and the shear forces induced within the soil due a potential slip circle, the CMCs can be susceptible to lateral loading, subsequently inducing a moment within the concrete column itself. The verification of the inclusion integrity in terms of axial force and bending moment in the column is carried out in accordance with the half-moon method shown in formula 3 below and derived from the Eurocode 2, section 12:

$$N_{Ed} \leq N_{Rd} = A_{ref}.f_{cd} \tag{3}$$

Where N_{Ed} = design value of the applied axial force; f_{cd} = design compressive strength of the CMC grout; A_{ref} = compressive area of the CMC section under vertical load and bending moment

As long as $N_{Ed} \leq N_{Rd}$, no additional measures are required. Should $N_{Ed} \geq N_{Rd}$, some potential solutions are as follows:

- Increased the thickness of LTP
- Reinforcement of LTP using techniques previously described in section 2 above (steel or polymers – Reinforced Earth)
- Reinforcement of column as necessary
- Include further shear reinforcement between CMCs detailing Soil Mixing

One example of a project with CMC supporting an embankment was the Forth Replacement Crossing (FRC) project in Scotland (2015). The project detailed an embankment of 6m height which was built on a soft soils up to 17m in thickness, reinforced with CMC of diameter 360mm.

The plane-strain finite element calculations showed an expected horizontal displacement of around 14cm at the edge of the embankment.

Implementation of a soil mixing trench reinforcement between CMCs allowed columns to remain at 360mm in diameter while also improving the stability factor of safety against failure.

4.3 *Commercial Structures & Warehouses*

The nature of the CMC technique increases the global stiffness of the native soil, therefore it allows structural engineers to reduce the thickness and subsequently the reinforcement required within slabs on grade.

Generally, slabs are designed using a subgrade reaction coefficient, kv, considering a homogenous soil. The influence of rigid inclusions induces a slight additional moment within the slab. However, a method of analysis of the moments transferred to structural slabs considering rigid inclusions and slab joints has been developed and is detailed within the ASIRI Recommendations for Design of Rigid Inclusions (2013). This method as per Racinais and Plomteux (2011), consists of separating the sum of moment into three separate parts.

The load cases are as follows:

- ‘ma’ – calculation of a slab on equivalent homogenised soil
- ‘mb’ – influence of rigid inclusions on a continuous slab without joints
- ‘mc’ – Interaction between rigid inclusions and joints

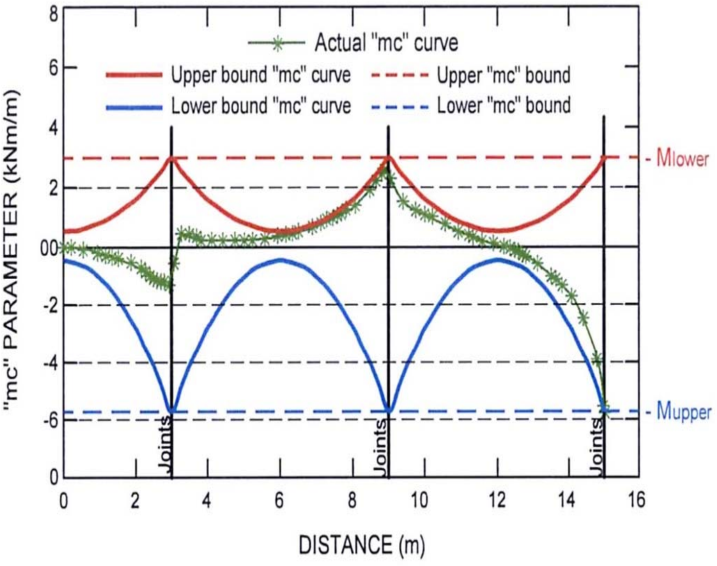

Figure 11. Bending Moment Envelope for Slab with Joints, ASIRI (2013)

This method is now commonly used in tandem with rigid inclusions with one such example being the recently constructed FM Logistics platform in 2015 in Moscow, Russia. The use of this design approach allowed for the reduction of the slab to 20cm with a reduced steel reinforcement on a soil profile that was often of a peaty nature with a depth profile in the range of 7m-14m of reinforcement.

4.4 *Wind Turbines*

CMC foundation solutions has seen an exponential growth in the Wind Farm industry in tandem with an increased requirement for governments to supply a minimum power source from renewable energies.

Turbine bases in terms of foundation design require the following specifications:

- Bearing Capacity
- Min Differential Settlement across the base
- Max Total Settlement
- Min Dynamic Rotational Stiffness, k_{dyn}

The largest combined Wind Farm in Europe, the Fantanele and Cogealac Wind Farms in Romania have both been developed using CMC foundations solutions. The project consisted of 250 turbines in total and the soil profile consisted of up 27m of loess deposits which were susceptible to collapse or bearing failure and large settlements.

4.5 *Quaywalls & Port Structures*

Soils in port locations can often have very poor characteristics. This can cause potential problems for the placement of modern quaywall structures which are sensitive to differential settlement due to more often than not, the presence of a gantry crane.

Figure 12. CMC Execution; Porto Di Vado

A successful installation of a CMC system was the recent Porto Di Vado Trial Project in Italy in 2014. Execution was carried out in offshore conditions in 20-30m of soft soils in the location of the proposed container terminal. A granular mattress was placed over the head of the CMCs. The caissons where then floated into place and positioned on top of the CMCs.

4.6 *Limitations*

As previously described, CMC is an ideal solution under uniformly distributed loads (UDL) such as embankments or warehouses however CMC may not be suitable for projects with highly concentrated loads such as:

- structures of G+10 and above
- foundations with very high overturning moments or lateral loading

In the case of high overturning moments or lateral loading, generally an increased isolated footing size can be a simple solution to replace a deep pile and pile cap with CMCs placed directly beneath the footing with or without a LTP. However, in some cases, for higher moments or overturning, the footing necessary becomes quite large and no longer would be considered feasible in a practical or financial sense.

5 CONCLUSIONS

The design, application and execution of the CMC Rigid Inclusion technique has been developed through intense research, development and design over the past 20 years. It has been shown to be effective across a wide range of diverse industries. By using the existing capacity within the soil the CMC has proved to be an efficient and economical alternative to traditional piling.

6 REFERENCES

AFPS-CFMS (2012). Procédés d'amélioration et de renforcement des sols sous actions sismiques – Guide technique, Presses des Ponts, Paris.

ASIRI National Project (2013). *Recommendations for the Design Construction and Control of Rigid Inclusion Ground Improvements*, Presses des Ponts, Paris.

BSI (2004). BS EN 1992-1-1:2004 Eurocode 2: *Design of concrete structures* Part 1-1: General rules and rules for buildings.

Hamidi, B., Nikraz, H & Varaksin, S. (2009), A Review on Impact Oriented Ground Improvement Techniques, *Australian Geomechanics Journal;* 44(2), 17-24.

Plomteux C. & Ciortan, R. (2010). Integrated Ground improvement solution for the largest wind farm project in Europe. *Proc 14th Danube-European Conference on Geotechnical Engineering 'From Research to Design in European Practice, 2010.* Bratislava, Slovakia.

Racinais, J. & Plomteux, C. 2011. Design of slab-on-grades supported with soil reinforced by rigid inclusions. *EYGEC;* Rotterdam: September 2011.

Racinais, J., Varaksin, S. & Yee, K. (2013). New approach to determine ultimate stress mobilization in the interface "rigid inclusion head and load transfer platform".

Yee, K, Setiawan, R.A., & Bechet, O, (2012). Controlled Modulus Columns (CMC): A New Trend in Ground Improvement and Potential Applications to Indonesian Soils. *ISSMGE – TC211 – International Symposium on Ground Improvement;* Brussels: 31 May & 1 June 2012.