Soil reinforcement by rigid inclusions under a clinker storage dome

Renforcement de sol par inclusions rigides sous un dôme de stockage de clinker

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ABSTRACT: As part of the project of the Ultracem cement plant, located in Galapa (Colombia), a concrete dome for the storage of 75 000 t of clinker was foreseen. This dome is 36 m high and based on a concrete ring beam of 60 m in diameter. This configuration leads to very high loads imposed at the surface level, up to 570 kPa at the center of the dome in operation. The foundation ground being composed of a succession of silty sand, sandy silt and silty clay layers overlaying a claystone base, it was necessary to reinforce it in order to prevent disorders due to differential post-construction settlements. A solution of rigid inclusions (Controlled Modulus Columns - CMC) arranged in a very dense grid was chosen. The purpose of this paper is to summarize the specific conditions of the project and detail the methods used to design the inclusion network (local analytical models and global finite element model). The execution procedures and the controls carried out on the jobsite are also presented.

RÉSUMÉ : Dans le cadre du projet de la cimenterie Ultracem à Galapa (Colombie), un dôme en béton pour le stockage de 75 000 t de clinker devait être construit. Celui-ci, d'une hauteur de 36 m, repose sur une couronne en béton de 60 m de diamètre. Cette configuration mène à des charges très élevées au niveau du sol, jusqu'à 570 kPa au centre du dôme en phase d'exploitation. Le sol de fondation étant composé principalement d'une succession de couches de sable limoneux, limons sableux et argile limoneuse reposant sur un socle d'argilite, il a été nécessaire de le renforcer afin d'éviter des désordres liés à des tassements différentiels post-construction. Une solution d'inclusions rigides (Colonnes à Module Contrôlé – CMC) réparties selon un maillage très dense a été retenue. L'objet de cet article est tout d'abord de résumer les conditions particulières du projet puis de détailler les méthodes employées pour le dimensionnement du réseau d'inclusions (modèles analytiques locaux puis modèle global aux éléments finis). Les conditions d'exécution des CMC et les contrôles réalisés pendant le chantier sont ensuite exposés.

KEYWORDS: CMC, rigid inclusions, storage dome, finite elements, analytical modelling.

1 INTRODUCTION

As part of the development of its facilities, Ultracem, a Colombian company specialized in the production of cement and concrete, decided to construct a new dome for the storage of clincker at its plant in Galapa, Atlántico (Colombia).

1.1 *Dome characteristics*

This dome, foreseen to store up to 75 000 tons of clinker, is a hemispherical reinforced concrete structure of 60 m in diameter resting on a cylindrical base of around 6 m in height. The clinker, with an average unit weight of 16 kN/m^3, will be stored in a conical shape with a maximum height at its center of more than 35 m, leading to loads up to 570 kPa at the foundation level. The dome structure itself applies a peripheral load of 625 kN/m. In addition, for operational purposes (transportation of the material), a 5 m x 5 m underground service gallery made of concrete crosses the dome along a diameter from South to North (see Figure 1).

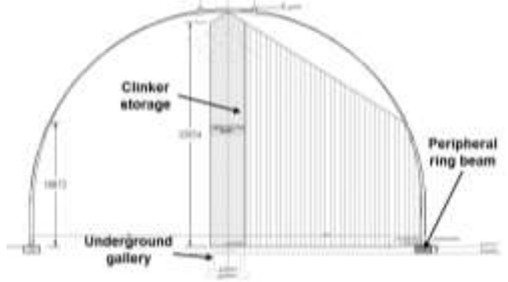

Figure 1. Cross-section of the dome

1.2 *Soil conditions*

The soil conditions were investigated through two campaigns comprising 14 boreholes located on a wide area with samples taken for classification tests (in 2012) and 6 cone penetration tests completed by 2 pressuremeter tests located in the close vicinity of the dome location (in 2015).

The typical soil profile consists of a 4.5 m to 10.5 m thick layer of medium dense to dense sandy silt or silty sand (q_c between 5 MPa and 30 MPa) overlying a 2.5 m to 7 m thick layer of soft silty clay (q_c between 0.1 MPa and 3 MPa). The substratum is made of claystone. The thicknesses of these layers vary however greatly on the whole footprint of the dome.

1.3 *Geotechnical issues*

Without any soil improvement, the very high and variable loads applied at the base of the dome, combined with the heterogeneity of the soil conditions, would lead to potential differential post-construction settlements along the ring beam or the underground gallery. These differential settlements could cause disorders incompatible with the standard operation of the facility. To mitigate these geotechnical issues and homogenize the reaction of the soil of foundation, a solution of reinforcement by Controlled Modulus Columns (CMC) was selected.

1.4 *Foreseen solution*

The ground reinforcement consists of a rigid inclusion network installed in the soil down to the load-bearing claystone layer and disconnected from the above structure by means of a load transfer platform: as such, both concrete inclusions and surrounding soil participate to the foundation system. On this project, the columns of diameter 400 mm are arranged in a particularly dense square grid of 1.25 m x 1.25 m to 1.45 m x 1.45 m. The load transfer mechanism is ensured by the presence of a platform under the structure made of compacted granular material. This layer has a thickness of 40 cm below the gallery, 50 cm below the ring beam and 1.2 m below the storage area.

2 RIGID INCLUSION DESIGN

2.1 *Methodology*

Due to the heterogeneity of the different soil layers and the distribution of the loads at the base of the dome, the gallery and the ring beam, the reinforcement area was subdivided in 9 subzones (see Figure 2 and Table 1).

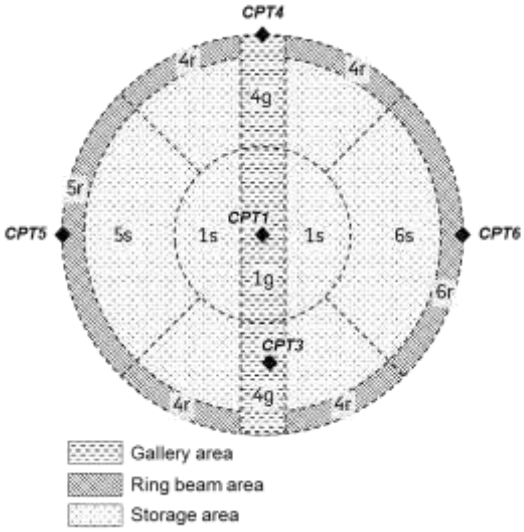

Figure 2. Zoning of the soil reinforcement

In the naming of the zones, the digit is related to the CPT, whereas the letter corresponds to the structure ('g' for gallery, 's' for storage area and 'r' for ring beam).

Table 1. Characteristics of the different zones

Zone	*Related CPT*	*Average load (kPa)*	*CMC grid spacing (m)*
1g	CPT1	606*	1.25
1s	CPT1	484	1.25
4g	CPT3/4	418*	1.45
4s	CPT3/4	364	1.45
4r	CPT3/4	330	1.45
5s	CPT5	364	1.45
5r	CPT5	330	1.45
6s	CPT6	364	1.45
6r	CPT6	330	1.45

**takes into account the gallery load*

It has to be noted that CPT3 and CPT4 show similar soil conditions, so that the problem can be considered symmetric in relation to the line joining CPT5, CPT1 and CPT6.

Using this subdivision, a specific analytical axisymmetric model has been developed for each zone. These calculations allow for the verification of the integrity of the rigid inclusions to compression and gives also as an output an equivalent Young's modulus of the reinforced soil.

These equivalent moduli, calculated for each zone, are then implemented in a 3D finite element model to check that the settlements (absolute and differential ones) are acceptable.

2.2 *Analytical local models*

To study the behavior of a regular mesh of columns under a uniformly distributed load, it is sufficient to focus on a unit cell comprising a single column and its surrounding soil (see Figure 3).

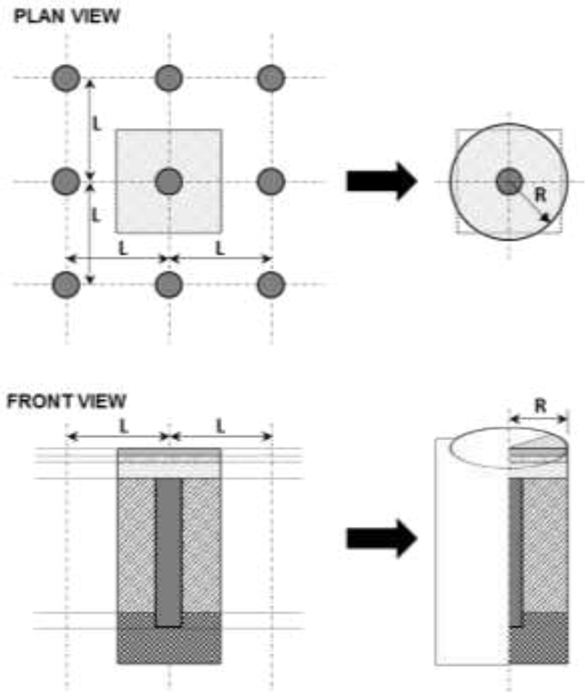

Figure 3. Principle of a unit cell axisymmetric model

The unit cell calculation is carried out in in accordance with an analytical biphasic model MV2 (ASIRI 2013). The calculation follows an iterative procedure: the stress distribution is adjusted until reaching the final condition of settlement equality directly below the slab.

This approach requires interactions between the « CMC » domain and the « SOIL » domain which are based on the following key principles:

- Interaction CMC head-LTP
  - Fictitious inclusion method (Combarieu 1988) for the evaluation of negative friction within the LTP;
  - Verification of the no punching according to the method based on the Prandtl diagram.
- Interface SOIL-CMC
  - Behavior laws of Frank and Zhao (Frank and Zhao 1982);
  - Values of limit friction defined as follows:
    - Negative skin friction: Ktanδ x $\sigma'_{v;soil}$ with Ktanδ an empirical factor which relates the shear stress and vertical stress along the CMC shaft, and $\sigma'_{v;soil}$ the vertical effective stress within the soil;
    - Positive skin friction q_s.
- Behavior at the CMC tip
  - Behavior laws of Frank and Zhao (Frank and Zhao 1982);
  - Values of limit end-bearing pressure below the CMC bottom q_b.

The outputs of the calculations are the distribution of the settlements within the soil and within the CMC, the distribution of the axial load and the distribution of the mobilized skin friction.

It is therefore possible to calculate an equivalent modulus of the reinforced soil over the whole length of the column as described hereinafter.

The oedometric modulus on the whole model height is by definition:

$$E_{oed,model} = \frac{\Delta\sigma . \mathrm{H}_{model}}{\Delta h} \quad (1)$$

On the other hand, by discretizing the model in different layers, we can use an harmonic average to define the modulus of the model:

$$E_{oed,model} = \frac{H_{model}}{\sum_i H_i / E_{oed,i}} \quad (2)$$

Consequently, the oedometric modulus over the height of the reinforced soil is:

$$E_{oed,rs} = \frac{H_{rs}}{\frac{H_{model}}{E_{oed,model}} - \sum_{i \neq rs} \frac{H_i}{E_{oed,i}}} \quad (3)$$

Using Eq. (1) in Eq. (3) leads to:

$$E_{oed,rs} = \frac{H_{rs}}{\frac{\Delta h}{\Delta\sigma} - \sum_{i \neq rs} \frac{H_i}{E_{oed,i}}} \quad (4)$$

In the above equations, $E_{oed,i}$ is the oedometric modulus of the layer 'i', H_i the thickness of the layer 'i', the subscript 'rs' refers to the layer of the reinforced soil, $\Delta\sigma$ is the applied load and Δh is the corresponding settlement.

Finally, the Young's modulus of the reinforced soil is calculated from the oedometric modulus using an equivalent Poisson's ratio:

$$E_{Y,rs} = \frac{(1 + \nu_{eq})(1 - 2\nu_{eq})}{1 - \nu_{eq}} E_{oed,rs}$$

Applying this procedure to the 9 cases presented in Table 1 resulted in the definition of 9 equivalent reinforced soils, with Young's modulus ranging from 83 MPa (zone 5s) to 235 MPa (zone 1g).

The unit cell calculation also enables the verification to compressive stress of the concrete. The maximum axial load in the column in SLS conditions is 822 kN (zone 1g), which represents a SLS stress of 6.5 MPa. This is therefore required to use a concrete of characteristic compressive strength at 28 days f_{ck} = 25 MPa, for which the maximum allowable SLS stress is 7.0 MPa.

2.3 *3D finite element model*

A 3D finite element model is then implemented in Plaxis 3D AE, with the representation of the dome foundation (ring beam) and the concrete underground service gallery.

The reinforced soil is modeled as a linear elastic model, with Young's modulus resulting from the axisymmetric unit cell calculations (9 different materials corresponding to the 9 subzones – see Figure 4). All other soil clusters are implemented as linear elastic perfectly plastic (Mohr-Coulomb) materials.

The storage load of the clinker is modeled as a distributed load and the load coming from the dome structure is represented by a linear load along the ring beam (see Figure 5).

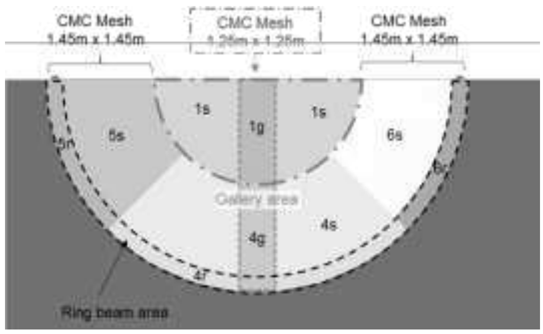

Figure 4. Top view of the 3D finite element model showing the 9 subzones

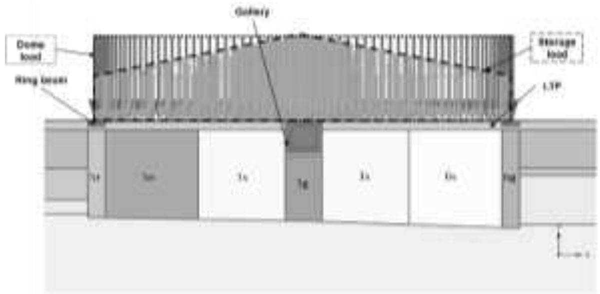

Figure 5. Vertical cross-section of the 3D finite element model showing the applied linear and distributed loads

The model consists of 31,017 elements with a total of 45,754 nodes (see Figure 6).

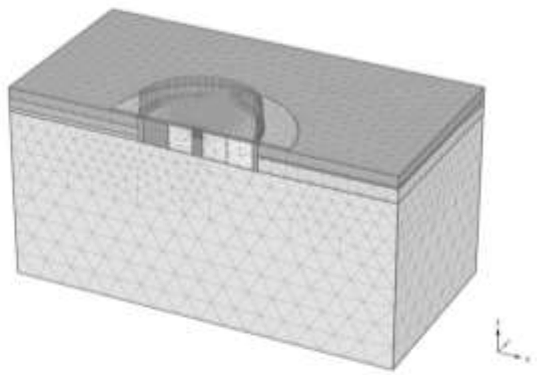

Figure 6. General view of the 3D finite element model

The calculations are carried out in 4 steps as described in Table 2, as plastic analysis.

Table 2. Calculation phases

Step #	*Description*
1	Stress initialization at natural ground level
	Reset of settlements
2	Installation of LTP, ring beam and gallery
	Reset of settlements
3	Construction of the dome
4	Application of the operation storage loading

Under the storage load (at the end of step 4), the maximum total settlement reaches 10.4 cm at the center of the dome (see Figure 7).

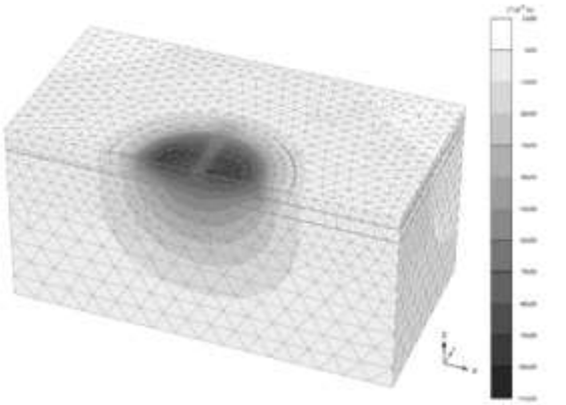

Figure 7. Total settlement at the end of step 4 from Plaxis 3D

The key verifications are however to be made in terms of diffential settlements, especially under the ring beam and under the gallery.

The values of settlements under the ring beam are extracted from Plaxis 3D and then plotted on a chart to verify that the angular distortion doesn't exceed 1/500 (see Figure 8).

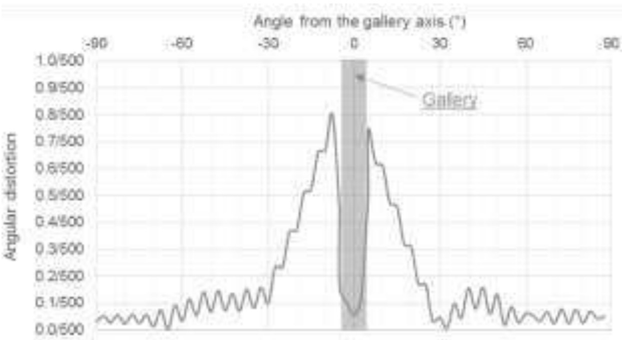

Figure 8. Angular distortion along the ring beam at the end of step 4

As for the gallery, the settlement varies from 5.9 cm to 9.0 cm (see Figure 9), resulting in an angular distortion in the longitudinal direction lower than 1/555.

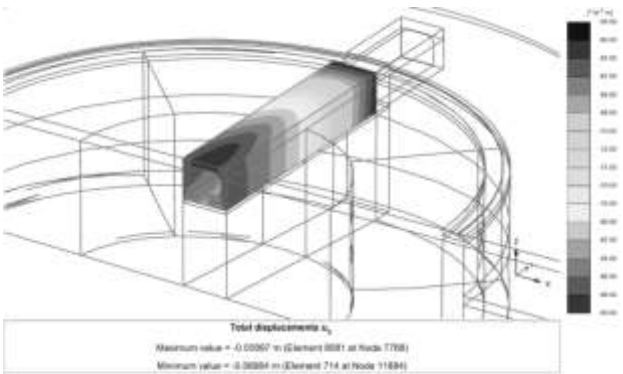

Figure 9. Total settlement in the gallery at the end of step 4

3 EXECUTION AND CONTROLS

Due to the stiffness of the soil and the high replacement ratio, it was not possible to use displacement auger so a classic continuous auger was used for the execution of the CMC.

In the center of the dome the work was performed 5 m below the site main elevation in order to install the rigid inclusions under the underground central gallery.

The columns of the two remaining areas were executed at the same time with two different machines alongside to the gallery building team. Due to the variations of the grid a special attention was given to the topographical location of the CMC.

The 1700 columns have been installed in two months. Slump tests were performed on fresh concrete at arrival on site and samples were taken to test the compressive strength and check that its value was in line with the design requirement.

After the construction (see Figure 10), topographic measurements on the ring beam and in the central tunnel are planned in order to follow the settlements during the future loading of the dome. These results will then be compared with the predictions.

Figure 10. Picture of the constructed dome

4 CONCLUSIONS

The use of soil reinforcement by rigid inclusions with a narrow spacing, even under very high distributed loads (up to 570 kPa), allowed to homogenize the reaction of the soil of foundation and therefore reduce the settlements to values compatible with the operational requirements of the clinker storage facility.

In order to optimize the soil improvement solution, a specific detailed design taking into account all the foreseen cases of *load* x *structure* x *soil condition* was carried out in two steps: analytical axisymmetric models to represent the different CMC configurations followed by a 3D finite element model to assess the global behavior of the structure in terms of settlements.

The works consisting in installing more than 1700 rigid inclusion from two levels of platform were performed in 2015, with a specific care in the quality control of the concrete. A monitoring of the settlement of the dome during the loading is planned and the resulting measurements will be compared with the predictions.

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