The application of Cutter Soil Mixing to an urban excavation at the riverside of Lagos, Portugal

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ABSTRACT

The Cutter Soil Mixing (CSM) technology consists of the execution of soil-cement panels through the soil disaggregation by mechanical action of two sets of cutting wheels that rotate around a horizontal axis while providing a cement slurry injection simultaneously. The CSM technology is a development of Deep Soil Mixing technique, using a hydromill to create soil-cement panels with a rectangular cross-section. Some advantages of this technology are the possibility to know the exact geometry of the soil-cement panels in depth, the effective connection between the panels and the possibility of the mixing quality control in real time. This paper describes the application of CSM to the construction of a temporary retaining wall for an urban excavation at the riverside of Lagos, Portugal. The paper describes the general aspects of the execution process and the main results of the instrumentation and monitoring work, which confirm the excellent performance of the adopted solution.

1. INTRODUCTION

Underground parking is a need in many cities and one of the advantages of the subsoil use is the possibility of the surface occupation with leisure areas. The work presented in this paper is a good example of the recognition of this necessity in the city of Lagos, Portugal, and it concerns the execution of a temporary retaining wall for the construction of the underground parking FUTURLAGOS, inserted in the Strategic Regeneration Plan of the riverside of the city (Figure 1).

Figure 1: Site plan.

In this paper is discussed the application of Cutter Soil Mixing (CSM) technology to the construction of the temporary retaining wall for the excavation of the underground parking lot. The solution consists of a continuous wall formed by CSM panels reinforced with vertical steel piles (IPE piles) with a level of ground anchors in the top.
This solution was presented as an alternative to the initial solution consisting of a concrete pile wall formed by piles of diameter 800 mm placed at 1.0 m intervals, with soil treatment by jet grouting columns in the pile ranges, also with a level of ground anchors in the top.

In Geotechnical Engineering and, particularly, in the context of soil improvement techniques one of the main concerns is the development of new solutions, technical and economically more attractive, with lower environmental impact. The use of the existing soil as a construction material through its mixture with cement slurry has been intensified and diversified over the time and new versatile and innovative techniques have been developed to achieve more sustainable solutions. In this context has been developed the CSM technology which is based on the use of the in-situ soil as a construction material to create soil-cement panels with a rectangular cross-section by the use of a hydromill. This technology is a new and effective method for the construction of cut-off walls, earth retaining structures, soil improvement and foundation elements.

2. THE PRINCIPLE OF THE CSM TECHNOLOGY

2.1. General description

The application of CSM technology consists of the disaggregation of the in-situ soil through the action of two sets of mixing wheels that rotate about horizontal axis while the cement slurry is simultaneously mixed into the existing soil. This creates soil-cement panels with the soil particles becoming the aggregates (Arnold et al., 2011).

CSM had a development based in some principles of Deep Soil Mixing (DSM), using also some implementation principles of diaphragm walls, in particular the hydrofraise.

Recent successful projects confirm that this is an interesting solution, with technical and economic advantages, already implemented in several countries (Gerressen et al., 2009).

Some advantages that make this technology competitive, particularly when compared with jet grouting and some traditional solutions of retaining structures are:

- the possibility of knowing the exact geometry of the panel in depth;
- the reduced vibrations during construction;
- the disaggregation of in-situ soil allowing to optimize the mixing process;
- the effective connection between panels even with different ages of construction;
- the very little generation of spoil;
- the possibility of execution in the presence of water table;
- the use of in-situ soil as a construction material;
- the possibility of application to all soil types, although not all kinds of soils are equally suitable.

This technology presents a better performance in soils like sand and gravel, but in soils like clay or silt the strength obtained with the same cement content is lower.

2.2. Execution Process

The application of this technology involves a construction process that must be adapted to the ground conditions and to the specific requirements of each project.

After the correct positioning of the equipment and the cutting head at the specified panel location, the cutting wheels are driven through the ground at a continuous rate until it reached the design depth.

During the cutting phase, the soil matrix is broken up and the cement slurry is added to fluidify the soil. The penetration speed of the mixing tool during this phase can be adjusted at any time to optimize the use of energy, according to the soil characteristics.

In difficult soil conditions or in the execution of deep panels, it may be necessary the use of bentonite during this phase and, in this case, the cement slurry is added just in the extraction phase. The second phase of the process consists of the extraction of the cutting head. The rotation direction of the cutting wheels is inverted in this stage and cement slurry is added to the homogenization of the mixture. The cement slurry added in this phase must be only the difference between the total quantity and the quantity already mixed in the cutting phase.

The CSM panels can be reinforced with vertical steel piles inserted into the freshly mixed soil-cement. The steel piles are inserted into panels of soil-cement by gravity or using vibration hammers.

A continuous CSM wall is formed by the execution of individual panels in an alternating sequence, overlapping primary and secondary panels. The distinction between primary and secondary panels is only related with the execution sequence. Figure 2 illustrates the main phases of the CSM execution process.

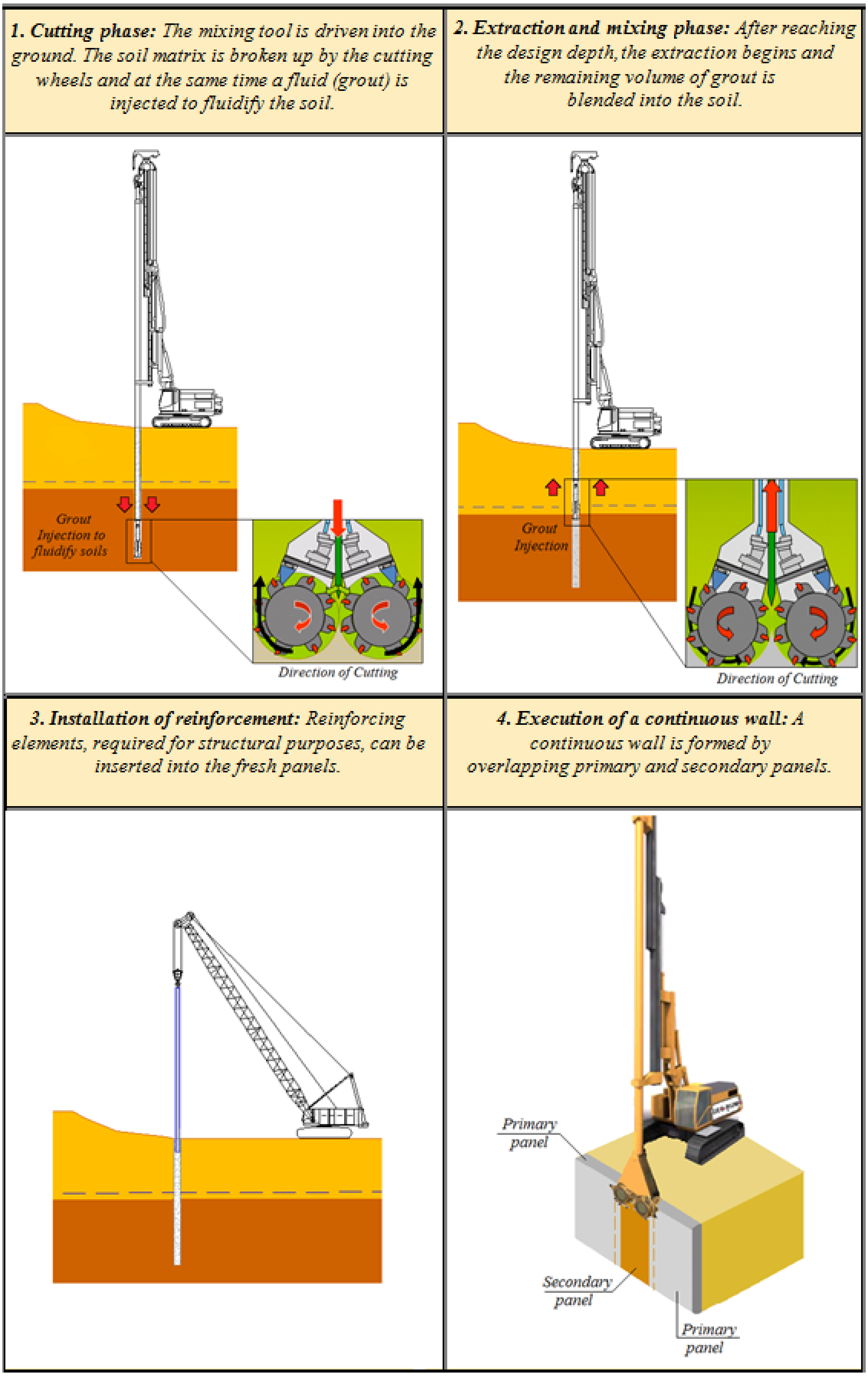
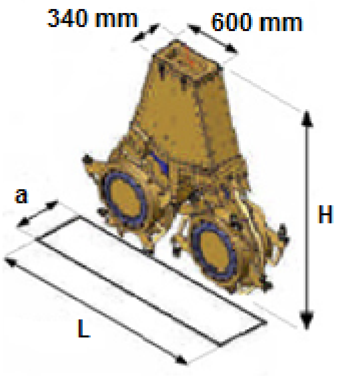


Figure 2: Illustration of the main phases of CSM execution process.

The main objective of this procedure is the improvement of the soil characteristics, through the increase of the resistance as well as the reduction of the permeability. The properties of the mixture obtained are reflected not only by the characteristics of the existing soil but also by the properties of the cement slurry added.

2.3. Equipment

The soil-cement panel dimensions depend only on the dimensions of the mixing head used. Figure 3 presents the characteristics of two models of mixing heads. Different types of cutting wheels and different types of cutting teeth allow the adaptation of the method to the different types of soils.



	BCM 5	BCM 10
Torque	0 - 57 kN.m	0 - 100 kN.m
Rotation speed	0 - 40 r.p.m.	0 - 35 r.p.m.
Weight	5100 kg (wheels 500 mm)	7400 kg (wheels 640 mm)
Heigh (H)	2.35 m	2.80 m
Panel length (L)	2.40 m	2.80 m
Panel width (a)	500 - 1000 mm	640 - 1200 mm

Figure 3: Characteristics of the Cutter Heads BCM 5 and BCM 10 (Bauer Maschinen).

The equipment enables the control of the following main parameters during the production (Lopez et al., 2005):

- cement slurry volume added;
- cement slurry pressure in hoses;
- slurry-soil pressure in trench;
- pumped volume in depth;
- pumped volume in time;
- inclination;
- speed of the mixing tool.

The documentation of the production process with respect to quality control is stored for subsequent evaluation. Figure 4 presents the monitor of the rig operator.

Figure 4: Rig operator's monitor to the control of execution parameters.

3. CASE STUDY

3.1. General description and Geotechnical conditions

The presented case study consists of the execution of a temporary retaining wall for the excavation of an underground parking lot at the riverside of Lagos, Portugal. The plan area of the excavation is about 6335 m^2, with a perimeter of 531 m (Figure 5) and a maximum depth of 6.0 m.

This parking, with two underground floors, has a construction area of about 12 670 m^2 and a capacity for 480 cars. The retaining wall consisted of a continuous CSM wall reinforced with vertical steel piles and a level of ground anchors in the top.

The work site is located near the marina of Lagos and is bounded to the northeast by an avenue, to the northwest by the building of the city's court and to the southwest by the ancient monumental fortress of the city.

The evaluation of the ground conditions was based on 12 geotechnical borings (Figure 5) to allow the execution of Standard Penetration Tests (SPT – S1 to S12), the installation of piezometers (Pz) and the execution of pumping tests (Pump) complemented with laboratory tests.

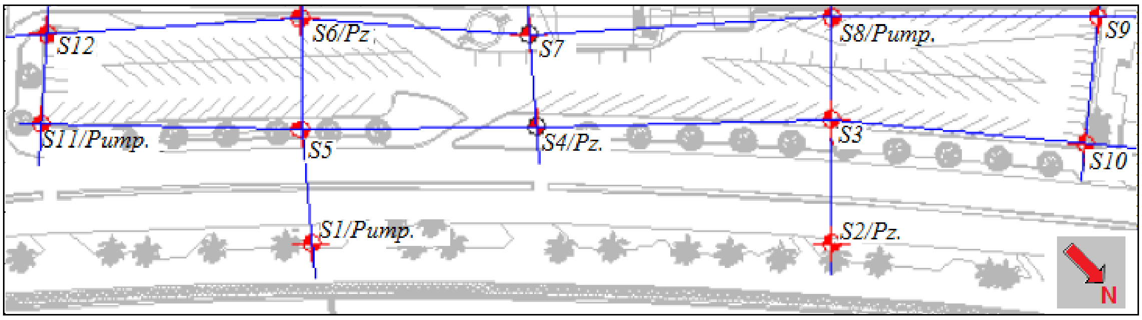


Figure 5: Location of the geotechnical borings executed to the evaluation of the ground conditions.

The ground at the site is composed by a sandy fill layer detected from the surface to a maximum depth of 6 m (N_{SPT} between 6 and 60, with global average value of 13), resting over the calcarenite substrate of the Miocene period (N_{SPT} between 7 and 60, with global value of 40). The tests carried out revealed a high heterogeneity of the soil in depth. The water table was detected near the surface with variations related to the tides. In Figure 6 is represented a geological-geotechnical profile with the SPT results of two of the boreholes executed (S11 and S12).

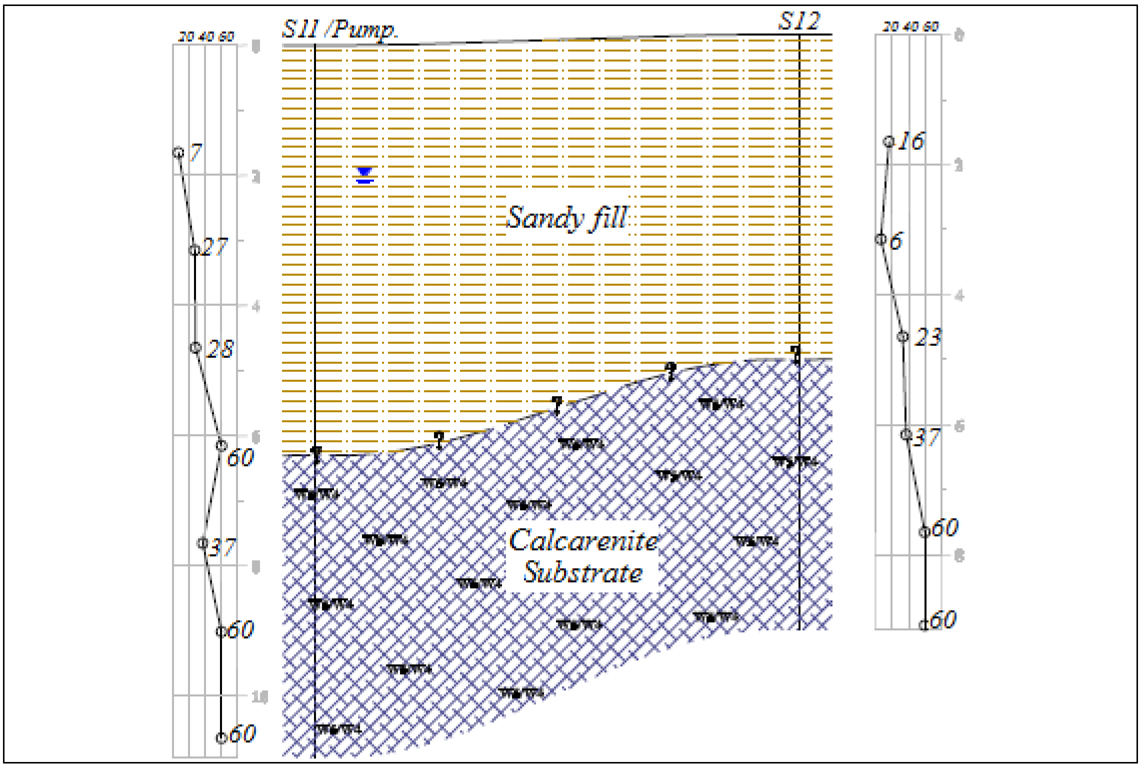


Figure 6: Geological-geotechnical profile (S11 and S12).

Table 1 presents the main geotechnical parameters, obtained by the interpretation of the in-situ and laboratory tests.

Table 1: Main geotechnical parameters.

	γ (kN/m3)	c' (kPa)	ϕ' (º)	E (MPa)
Sandy Fill	19	0	28	14
Calcarenite Substrate	20	10	30	42

3.2. CSM Retaining Wall

The adopted solution consisted of a peripheral CSM retaining structure executed to allow the vertical excavation, while ensuring the stability of nearby structures and infrastructures and reducing the inflow of water into the excavation during the construction phase.

The CSM panels were reinforced by vertical steel piles (IPE 330) and it was defined one level of ground anchors in the top. The retaining wall, 0.60 m thick, was composed of 262 CSM panels, in an alternating sequence of overlapping primary and secondary panels. The overlapping between them was 0.20 m. The vertical steel piles were installed at 0.70 m intervals, as close as possible to the excavation face.

In the crown of the CSM panels was executed a concrete beam to allow the application of the prestressing in ground anchors. Along the perimeter of the retaining structure were executed 196 ground anchors, with an inclination of 35º and a horizontal spacing of 2.5 m, with a design load of 600 kN. For the definitive stage was performed a concrete wall placed against the CSM wall.

Figures 7 and 8 present the structural solution defined to the retaining wall.

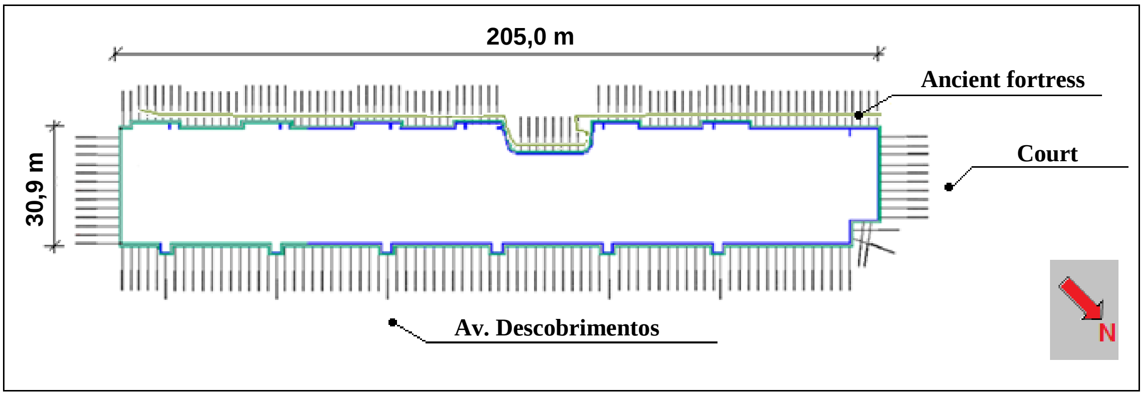


Figure 7: Plan of the excavation and surrounding conditions.

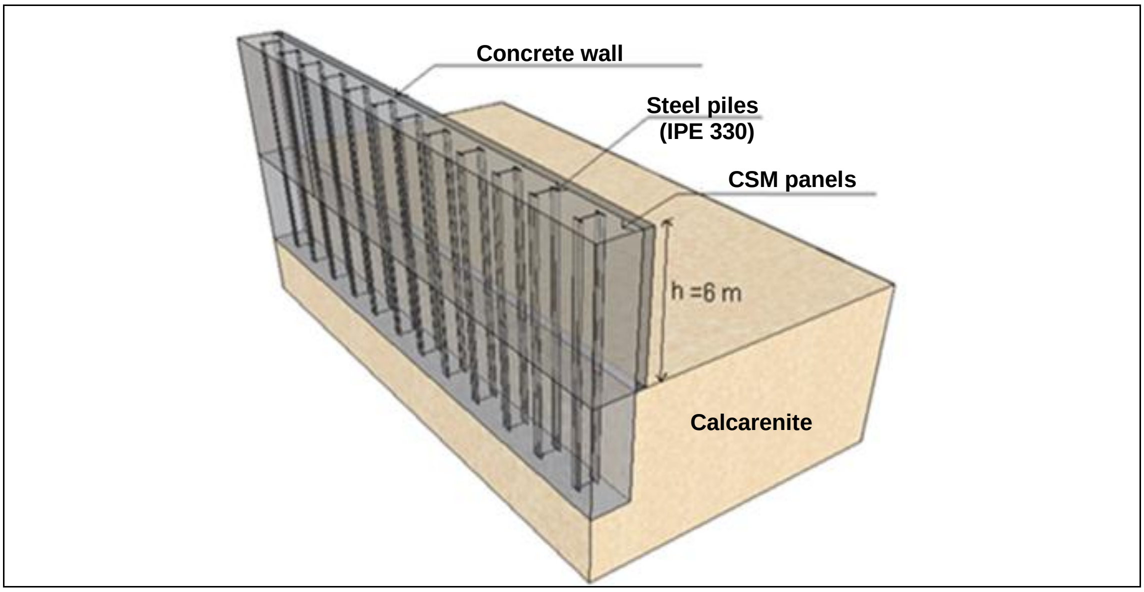


Figure 8: Structural solution: 3D view of the retaining wall.

3.3. Construction monitoring and observation of the work

3.3.1. Excavation and drainage system

Throughout the diferent excavation stages, no water inflow from the outside to the inside of the excavation through the CSM panels was observed. However, with the progress of excavation, the inflow of water occured from the bottom of the excavation, trough the calcarenites, and it was controlled by a temporary drainage system. With this aim, were executed 14 pumping wells, interconnected by a mesh of drains distributed along the excavation area. The pumping wells were installed gradually as the avancement of the excavation, according to the water volume to draw. This system was desactivated after the excavation works with the implementation of the definitive drainage system.
Figure 9 presents some views of the work during the excavation.

Figure 9: Views of the work during the excavation: a) excavation of 6 m depth; b) detail of the CSM wall; c) regularization of the bottom of the excavation.

3.3.2. Quality control

In the aim of the quality control, some CSM test panels were executed in advance, to obtain samples for laboratory tests. This procedure allows the calibration of the equipment before starting the execution of the retaining wall panels. Once the execution of the retaining wall started, quality control was provided by laboratory tests on samples from the panels of the CSM retaining wall.
The laboratory tests performed were:

- unconfined compressive strength tests;
- Brazilian tests.

A total of 36 samples were submitted to laboratory tests. The results obtained were a compressive strength of 3.1 MPa, a tensile strength of 0.3 MPa and an elasticity modulus of 2.9 GPa (average values). Figure 10 presents some of the samples during the laboratory tests.

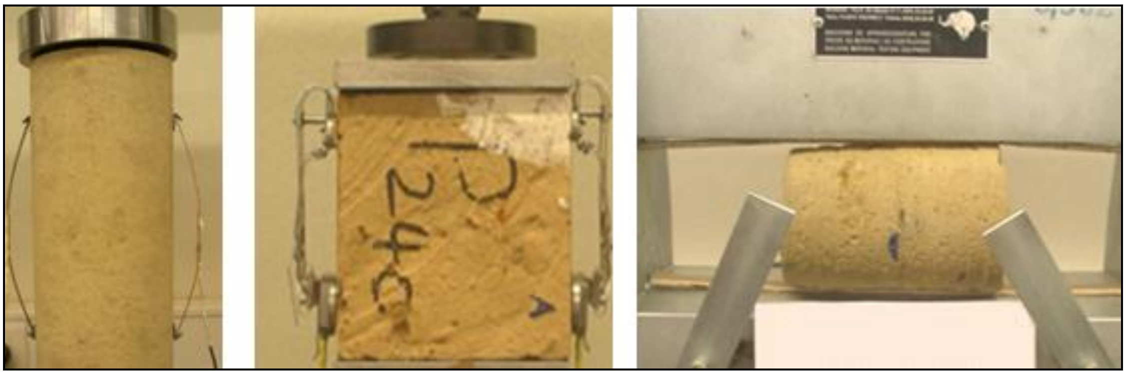


Figure 10: Laboratory tests.

3.3.3. Monitoring Plan

The monitoring plan was established to allow the control of horizontal and vertical movements of the wall and the load variation on the ground anchors through the construction process.
The location of monitoring instruments was defined according to the Figure 11.
The implemented monitoring instruments were:

- 5 inclinometers installed behind the retaining wall;
- 5 load cells installed in the head of the ground anchors;
- 17 surveying targets installed in the concrete beam in the top of the retaining wall.

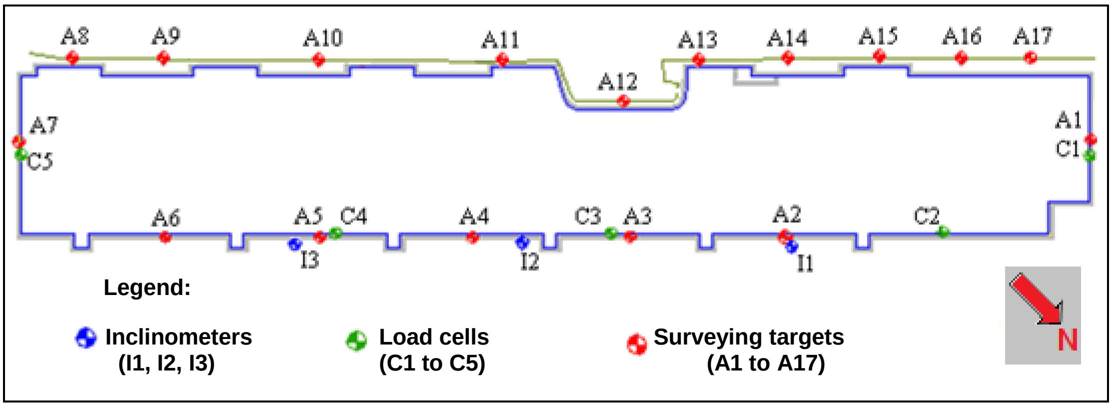


Figure 11: Location of the monitoring instruments.

There were performed five measurements of the inclinometers during the excavation. In Figure 12 are represented the envelope of the horizontal displacements obtained in the inclinometers I1, I2 and I3. The movements of the wall towards the excavation are represented by the positive values.

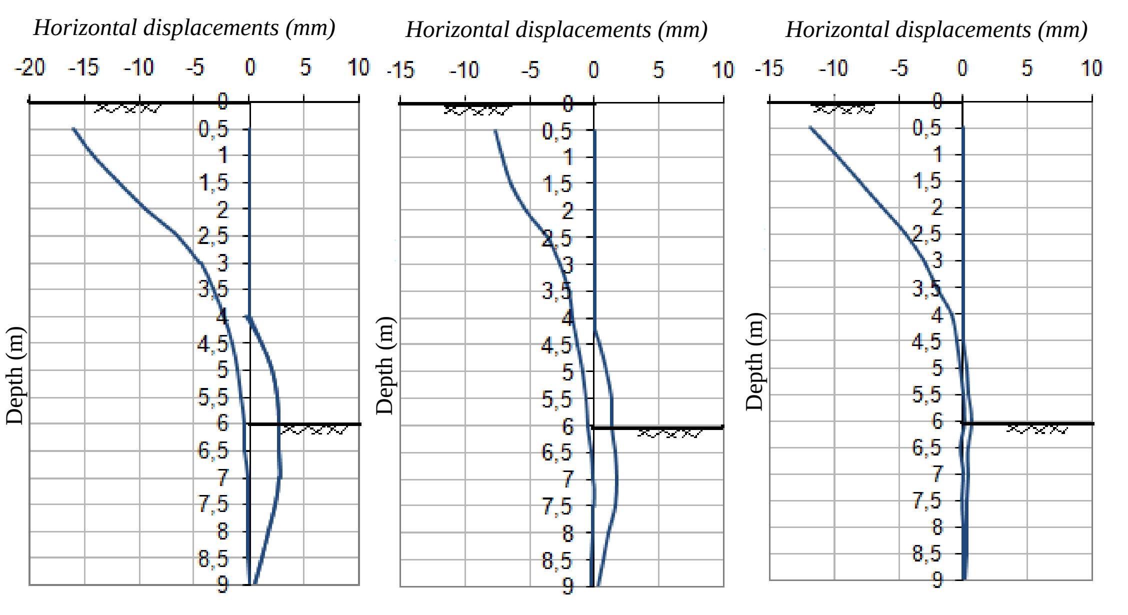


Figure 12: Envelope of the horizontal displacements: a) inclinometer I1; b) inclinometer I2; c) inclinometer I3.

The horizontal displacements globally present low values in every phases of the execution process. The recorded values were lower than the alert limits. The maximum values occurred in the last phase of the excavation, for a depth of excavation of 6.0 m (H).
The horizontal maximum displacement (δH_{max}) towards the excavation was about 3 mm and the maximum horizontal displacement in the opposite sense was about 16 mm.
Considering the movement of the wall in the opposite sense of the excavation, ($\delta H_{max}/H$) is about 0.27 % and considering the movement of the wall towards the excavation, ($\delta H_{max}/H$) is about 0.05 %. These values are in accordance with those observed in similar conditions in excavations with satisfactory performance (Clough and O'Rourke, 1990).
The measurements of the load cells were done in the following phases:

- Measure 1: after the prestressing of the ground anchors;
- Measure 2: after reaching an excavation depth of 3 m;
- Measure 3: after reaching an excavation depth of 6 m;
- Measure 4: before the execution of the permanent underground parking structure.

In the following table are compiled the results obtained through the measurements of the load cells.

Table 2: Results obtained through the measurements of the load cells.

Load in the ground anchor (kN)					Variation of load on ground anchor	
Load cell	Measure 1	Measure 2	Measure 3	Measure 4		
C1	640	590	590	590	- 50 kN	(7.8 %)
C2	640	545	545	540	- 100 kN	(15.6 %)
C3	550	510	510	500	- 50 kN	(9.1 %)
C4	620	580	580	580	- 40 kN	(6.5 %)

After the prestressing of the ground anchors, the installed load presented the minimum value and, with the advancement of the excavation, there was a slight increase of the load until its stabilization for an excavation depth between 3 m and 6 m.
The results are consistent with the variation of the horizontal displacements of the retaining wall because, after the prestressing of the ground anchors, there was a movement of the top of the wall in the opposite sense of the excavation and a subsequent decrease of the load on the ground anchors. The load tends to stabilize over the time.

The observation of the surveying targets led to satisfactory values of vertical displacements (settlements) of the retaining wall, presenting a maximum value of 9 mm.

4. CONCLUSIONS

This paper demonstrates that the application of Cutter Soil Mixing in the construction of a large underground parking in Lagos, Portugal, allowed a quite satisfactory behaviour in terms of stability and deformations, as well as the reduction of the water inflow to the interior of the excavation.
It should be pointed out the good performance even under demanding ground and water table conditions.
The horizontal and vertical displacements of the CSM wall during the excavation process presented low values. The maximum horizontal displacement towards the excavation was about 3 mm and the maximum horizontal displacement in the opposite sense was about 16 mm. The movements of the CSM wall were always lower than the alert limits defined.
The good results using CSM technology depending on several factors such as geological and geotechnical conditions, the specific requirements of each project, the experience of the engineers, the availability of appropriate equipment and qualified staff, among others. The control and monitoring of the works is particularly important, especially in the application of CSM technology in urban areas because there are a lot of factors which may influence the construction process. The implementation of an efficient monitoring plan and control allows to the application of preventive measures, reducing the risk for the neighbouring buildings and structures.

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