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Masters in Civil Engineering

Extended Abstract

# Behavior Analysis of a Berlin-type Retaining Wall

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# 1. INTRODUCTION

Urban construction often involves the execution of underground floors. Due to often existing surrounding construction, vertical excavations have to be executed, supported by a retaining wall. In such context, Berlin-type walls are one of the most suitable techniques to the execution of retaining walls in Lisbon.

This technique takes advantage of the construction phasing in order to minimize walls and back soil displacements. Under this perspective, it is important that the design guidelines are accomplished and, specifically, the construction phasing.

In this work the detailed execution of a Berlin-type wall in Lisbon is described. A quality control of the construction phasing was performed, aiming at detecting design deviations to the design guidelines. The information collected was crossed with the displacement graphics in order to find out design deviations that could have had direct influence on displacement variations.

Then, the influence of some of these construction phasing deviations on the displacements is simulated through simple calculations and also through the finite element method.

In this study several examples of the application of the observational method are shown.

# 2. BERLIN-TYPE WALLS

## 2.1. APPLICATION FIELD

Berlin-type walls are flexible, anchored, reinforced concrete structures.

This solution is not suitable to all kinds of soils. Soils with undrained behaviour are required, allowing the execution of vertical cuts with width and height usually between 2 and 4m. In addition, this technique does not apply to situations in which groundwater level is near the surface.

## 2.2. CONSTRUCTION PROCESS

### 2.2.1. Installation of steel sections

First of all, the holes are opened with a drilling machine. Afterwards, the steel sections are installed vertically and must be controlled. In order to connect the steel sections to the top beam, 0,5 m of steel should be left over the surface. Steel sections are, in most cases, H type (Brito, 2001).

### **2.2.2. Execution of the top beam**

Before placing the reinforcement, a sand layer is spread on the bottom. This sand layer will avoid the contact of the concrete with the soil and will also conserve starter bars to the panels that will be executed under the beam. Afterwards, it is time to position the reinforcement, being the steel sections centered inside it. Then the beam is shuttered and, consequently, the concreting may start.

### **2.2.3. Primary panels**

The process continues with the excavation of the primary panels. Only after the execution of the primary panels, can the secondary panels – which are located between the primary - start to be excavated. This process is repeated level after level until the desired depth is achieved.

In general, the width of the primary panels is the distance between two consecutive steel sections. On this basis, the excavation width will be that distance plus nearly 0,5m for each side to allow space for the starter bars. There will be two adjacent benches of soil on each side of the excavation that will withstand the tensions released by the soil decompression – arch effect.

Then the reinforcement is placed. As stated before, also in this phase a sand layer should be placed on the bottom. The reinforcement is generally assembled at the building site and then placed on the panel with the help of lifting equipment. Near the anchors insertion point shear punching and bending steel reinforcement are settled. Then follows the shuttering of the panel. The formwork should be sustained by a shoring system that is braced on the soil. The side formwork consists of small wooden planks placed between armours, working as tampons. Then, concreting can start. This process is done from the top of the panel, using a concreting hose or a hooper.

Afterwards, the anchor hole is drilled. This operation is carried out by a drilling machine (Figure 1). Then, the prestressed cables are introduced on the hole. The next step will be the sealing of the hole – primary injection. In this phase, it is injected cement grout that will cover the space between the anchor and the hole walls. Next, the bulb pressure is created. After, at least, 3 days till the prestress can be executed. The tensioning of prestressed cables is done recurring to hydraulic jacks. In order to minimize prestress losses, the tensioning of anchors is ruled by the program defined on the design. The prestress is controlled by a pressure gauge.

Following the main principle, secondary panels are now executed. Secondary panels are located between primary panels, being these now sustaining the soil stresses. The execution of secondary panels is similar to the execution of the primary ones.

### 2.2.4. Execution of the wall footing and superstructure

Having the last level of the retaining wall been executed, it is time to deal with the wall foundation. This footing will sustain, at a definitive stage, all the load coming from the retaining wall and also form the superstructure. Usually, the footing is executed by sections.



Figure 1 - Drilling machine working on a primary panel

## 3. CASE STUDY: “QUINTA DO MINEIRO” EXCAVATION

### 3.1. GENERAL DESCRIPTION

The execution of “Quinta do Mineiro” retaining wall was the case study within this work. The work is located in Lisbon, Artilharia 1 Street. The general contractor is *Engiarte*, being *Tecnasol* awarded with the retaining wall subcontracting - design and execution.

The building will be used as luxury housing, consisting of 7 floors and 6 underground floors that will be used for parking.

The excavation covered a total area of about 4600 m<sup>2</sup>, involving the removal of a total volume of soil of nearly 90000 m<sup>3</sup>. The general levels of excavation vary between 82.3m and 83.7m that corresponding to retaining heights between 7m and 20m, approximately.

#### 3.1.1. Geological-Geotechnical Constraints

Geological-geotechnical constraints were estimated based on the prospecting campaigns done on March 2000 and between July and September 2004.

The geotechnical parameters for each zone are presented in Table 1.

**Table 1** - Geotechnical parameters obtained from the prospecting campaigns (TECNASOL 2010).

Geotechnical parameters		Landfill (ZG1)	Miocene (ZG2A)	Miocene (ZG2B)	Cretaceous (ZG3)
Type		topsoil	sandy-clayey	sandy-clayey	calcareous
$\gamma$	[kN/m <sup>3</sup> ]	17.5	18	19	19
E	[kN/m <sup>2</sup> ]	7500	35000	65000	100000
v	[-]	0.3	0.3	0.3	0.3
c	[kN/m <sup>2</sup> ]	1	20	40	40
$\phi$	[°]	28	30	32	35
(*) $\gamma$ – volumetric dry weight; E – Young’s modulus; v – Poisson’s ratio; c – cohesion; $\phi$ - shear strength					

### 3.2. PROPOSED SOLUTION

In the solution proposed by Tecnasol the excavation had to be executed with the help of a retaining wall, constituted by reinforced concrete anchored panels, provisionally sustained by vertical steel sections. The technique proposed to execute the retaining wall was Berlin-type.

#### 3.2.1. Design Notes

All design guidelines were consulted. In this phase, only the design indications that were unfulfilled during the execution of the retaining wall are referred (Table 2). These indications refer to the construction process in general, but some of the indications refer specifically to construction phasing.

#### 3.2.2. Monitoring Plan

A plan to monitor the retaining walls was implemented. The designing options could be confirmed through the monitoring plan, given that indications related with the behavior of the site and its surroundings were permanently coming out. It was decided that topographic marks should be placed on the retaining wall as well as on the surrounding buildings to measure displacements.

The limits established by *Tecnasol* were the following (TECNASOL 2010):

- Alert criteria: maximum horizontal displacement is 25mm and the maximum vertical displacement is 15mm.
- Alarm criteria: maximum horizontal displacement is 35mm and the maximum vertical displacement is 25mm.

#### Observational method

During an excavation of this dimension, it is crucial to permanently monitor the soil. In parallel with this, it is important to ensure a permanent visual observation of the site, that might allow

the perception of possible changes on the retaining wall elements. This visual inspection must be done by anyone responsible of the site (foreman or site manager). Situations like the appearance of cracks, water pouring from the anchors or the appearance of types of soils not in line with the design phase are indicators of failures to the construction phasing or the existence of design errors that must be rectified (EUROCODE 7).

The results of the monitoring must be analyzed in proper time during the excavation and, in case the limits are exceeded, the designed contingency plan is activated.

**Table 2** - Summary of design indications subject of deviations ((TECNASOL 2010).

Summary of design indications subject of deviations	
1)	The execution of secondary/tertiary panels takes place only after the conclusion of primary/secondary panels that are adjacent to the first ones.
2)	Immediately after the minimum waiting time for concrete hardening, the anchor should be tensioned.
3)	The retaining wall thickness must be 0,4m.
4)	For each level, tasks must start with the execution of primary panels, followed by the execution of secondary panels and at last takes place the execution of tertiary panels.
5)	Each panel will be executed after a localized excavation.
6)	With exception of justified situations, there will be no simultaneous execution of two consecutive primary panels, leaving only one secondary panel in the middle.
7)	According to the characteristics of the soils, the time span necessary between excavation and concreting of each panel must not exceed 12 hours.
8)	Anchors and shorings deactivations must be done only after the execution of the underground slabs.
9)	Installation of load-cells in some anchors of the retaining wall.
10)	In cases of high water inflow to the inside of the excavation must be created a mechanism that makes water drainage possible.

## 4. DESCRIPTION AND ANALYSIS OF THE EXECUTION ON SITE

The main purpose of analyzing the execution of different fronts from the retaining wall is to achieve deviations to what is specified on the design. Fronts FG and BC are analyzed.

### 4.1. FRONTS FG AND BC

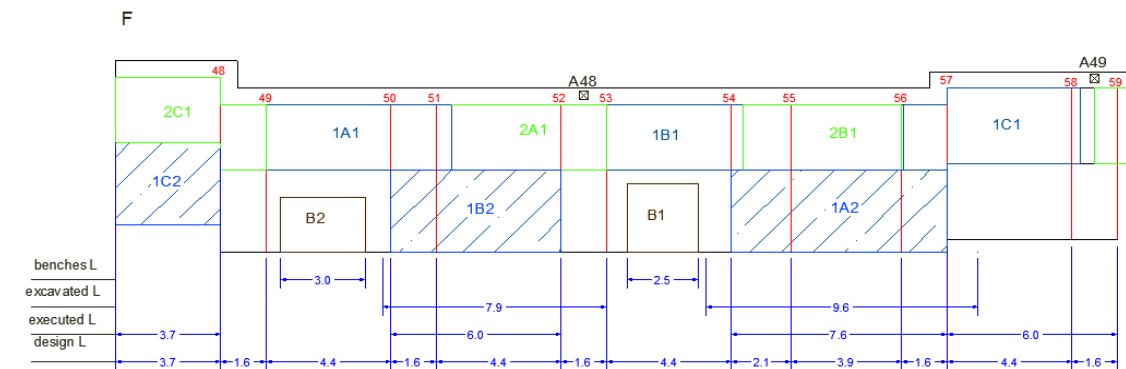
During the execution of front FG it was verified, at all levels, that the panel excavation length as well as the panels were larger than defined in the design. This can be observed on Figure 2 where a concreted panel is shown. Besides that, it was also observed that the majority of the benches left between panels on execution had lower dimensions than defined on the design

notes (see Figure 2). The benches observed occupy, in most cases, much less space than the one that is free for the purpose.

Back to the length of the panels executed, Figure 3 shows the panel length of the second level.



**Figure 2 – Primary panel executed (level 1 – FG front)**



**Figure 3 - Panels and benches lengths – FG front – 2<sup>nd</sup> level**

It is shown that the panel 1A2, for instance, has an excavation length which is 360% higher than the panel design length. At the same time, the panel executed length is 260% higher than the panel design length. The same situation was verified on BC front. For instance, the panel 2A4 excavation length is 240% higher than the panel design length. Regarding to the panel executed length, it was verified that it 190% higher than the panel design length. The panel 2A4 is shown on Figure 4.

It was observed, at the FG front, that panel 2C2 was excavated while the adjacent panel – 1C2- was being concreted. During the execution of FG front it was observed that panel 1B4 was excavated without the tensioning of the panel located on top of it.

During the execution of both fronts, it was verified that secondary panels were excavated before the tensioning of the adjacent primary panels. This situation had an exception on the 1<sup>st</sup> level of BC front. It was also verified, especially on BC front, that some anchors were executed a few centimeters (20-40cm) over the insertion point established on the design.



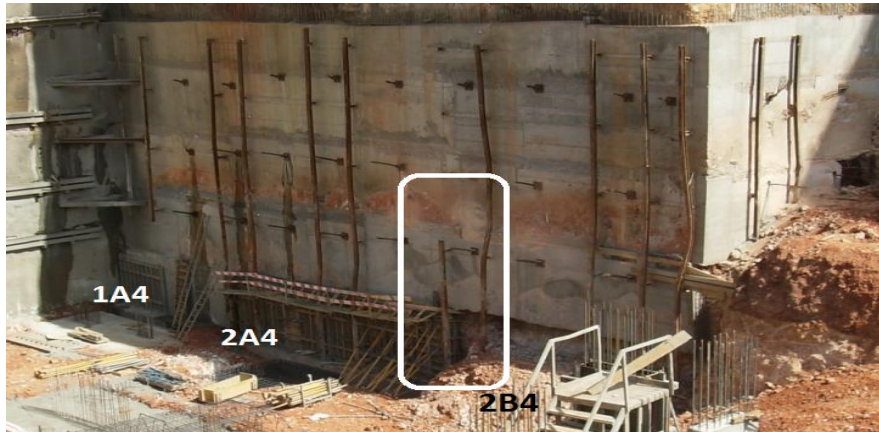


Figure 4 – BC front execution – 4th level

It was verified, on front FG that the wall thickness was larger than 0,4m. In average, the wall thickness of FG front was 53cm, value that is 33% higher than the wall thickness in design. This parameter was not measured on front BC due to access difficulties.

As it can be seen on Figure 4 one of the steel sections (nº7) was removed by an excavation machine.

On side FG, was verified, that the length of the executed panels exceeded, on average, almost in 215% the design length value. The same analysis regarding BC front indicates that the length of panels exceeded, on average, about 150% the design length value.

After the analysis of bench volumes on both fronts, it was concluded that, on front FG, the bench average volume is only 50% of the soil volume existent for the purpose while on BC front it was 70%.

### 4.2. DESIGN DEVIATIONS

All the situations observed that did not follow the design guidelines are summarized in Table 3.

### 4.3. ANALYSIS OF THE WALL DISPLACEMENTS

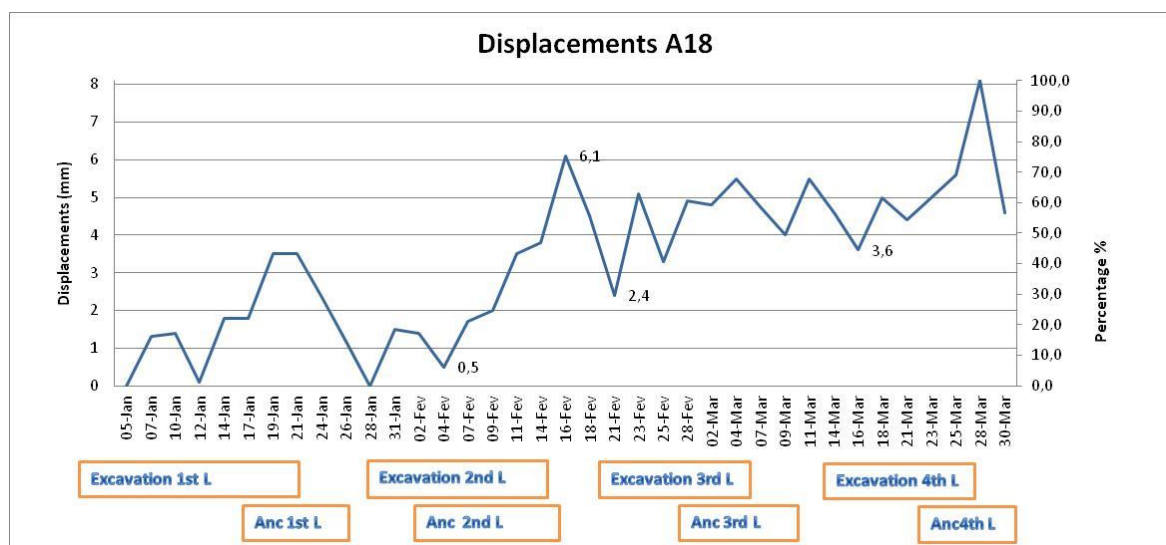
#### 4.3.1. BC front: Mark A18

The horizontal displacements A18 mark is analyzed. The aim is to identify the situations that have stronger influence on the displacements evolution. Figure 5 shows the evolution of the horizontal displacements measured on mark A18. In general, the periods with substantial increase of displacements match with excavation periods. This fact is only not observed on the 3<sup>rd</sup> level excavation, where displacements increases were softer. In fact, the large increase noticed was during the excavation of the 2<sup>nd</sup> level, where displacements grew 6,1mm. At the same time, it is verified that periods when displacements decrease or keep constant coincide with anchor tensioning phases. As stated before, the 1<sup>st</sup> level was the only one where primary

panels anchors were tensioned in the correct time defined in the project. In fact, that can be seen on the figure, through the recovering of displacements observed during the execution of the 1<sup>st</sup> level.

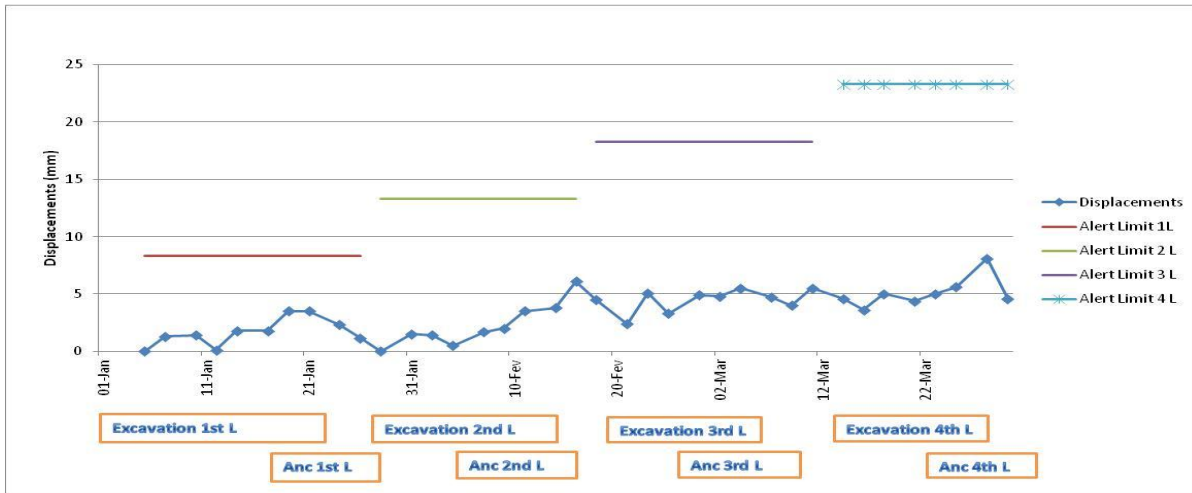
**Table 3 - Design deviations observed.**

Design deviations observed		FG	BC
A	Panels excavation length clearly exceed panel design length	✓	✓
B	Panels execution length clearly exceed panel design length	✓	✓
C	Deviations in the execution according to Design sequence (primary, secondary and tertiary panels)	✓	✓
D	Benches length smaller than the effective length free for the purpose	✓	✓
E	Secondary/tertiary panels excavation without adjacent primary/secondary panels tensioning	✓	✓
F	Secondary panel excavation while adjacent primary pane is being concreted	✓	✓
G	Failure of Design indication recommending a maximum time of 12 hours between excavation and panel concreting	✓	✓
H	Anchors disorganised execution	✓	✓
I	Panels over thickness	✓	
J	Panel excavation under panel still in concrete-hardening period	✓	
K	Panel excavation without tensioning upper panel	✓	
L	Steel section damage and removal		✓
M	Steel section buckling	✓	✓
N	Anchors deactivation before the execution of underground slabs	✓	✓
O	Non installation of load-cells on anchors	✓	✓
P	Deviations on anchors position	✓	✓



**Figure 5 – Horizontal displacements evolution.**

Figure 6 compares the horizontal displacements verified with each alert level limit. It is observed that, at no point, the alert limits are reached. The closer situations are on the first two levels, where displacements reach nearly 50% of alert limit values.



**Figure 6 – Horizontal displacements vs alert limits.**

### 4.4. GENERAL COMMENTS

During the observation next to FG front, it was verified that the geological composition of the intersected soils largely matched the design information. The geological profiles confronted, based on previous prospects, had wide correspondence with the excavated soil.

The analysis of vertical displacements permitted to confirm that anchor tensioning has great influence on its increase. Vertical displacements verified were way smaller than horizontal ones, being 6mm the maximum displacement measured. In addition, it was observed that the removal of one of the steel sections on BC front directly influenced the vertical displacements.

Regarding horizontal displacements in surrounding buildings, the maximum value measured was 5mm, which is far smaller than the limit.

## 5. SENSIVITY ANALYSIS

The major aim of this chapter is to establish correlations between deviations to the project identified before and displacement evolution.

### 5.1. EXCAVATION FACE – BENCH RATIO INFLUENCE ON STRUCTURE HORIZONTAL DISPLACEMENTS

As mentioned before, wider excavation faces and narrower benches were observed during the execution of the wall. Ground pressure and benches maximum resistant force are evaluated, at different excavation stages. The ratio between these two forces referred as  $req$  was calculated for each stage analyzed. These calculations were done using Terzaghi and Peck diagrams (Guerra, 2008). Relative displacements increases between stages are measured. Four different stages were analyzed, each one belonging to each excavation level are presented in Figure 7.

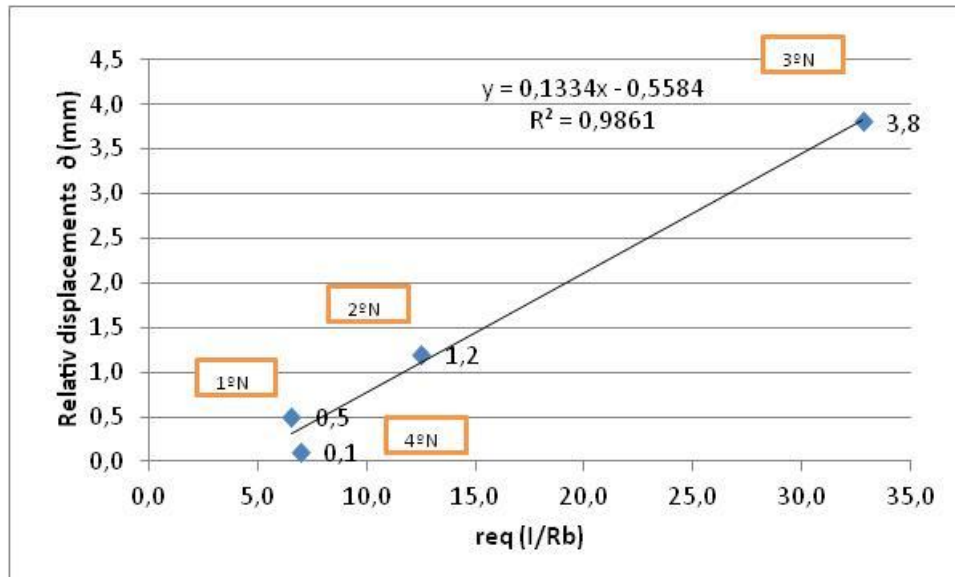


Figure 7 – Relation between relative horizontal displacements (measured on A18) and excavation face – bench ratio.

The figure shows that, despite ground conditions get better with depth, displacement increase by level grows with *excavation face – bench ratio* (req) increasing.

## 5.2. FREE SPAN BETWEEN BENCHES INFLUENCE ON STRUCTURE HORIZONTAL DISPLACEMENTS

It was verified, during the excavation that free span (VI) between benches increased with depth. The graph on Figure 8 shows the correlation between free span and the relative displacements on each level.

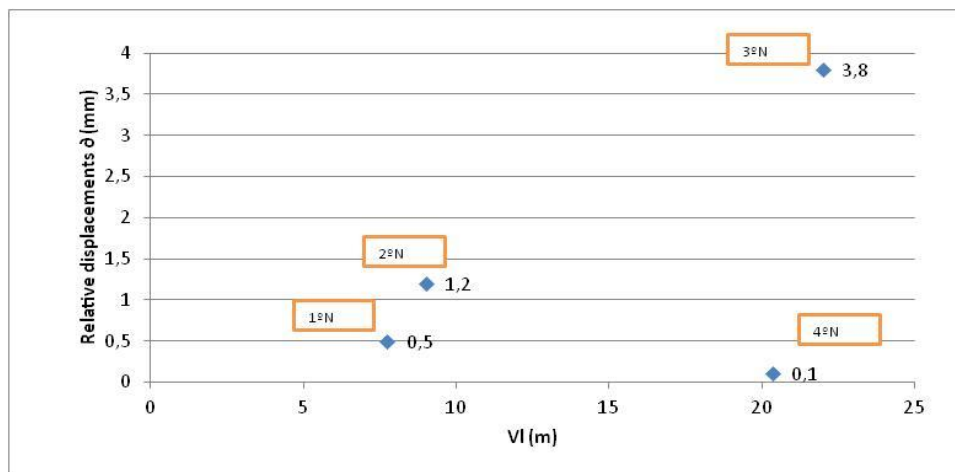


Figure 8 – Correlation between relative horizontal displacements (measured on A18) variation with free span variation in depth

It is verified an increase of horizontal displacements with the free span growth while the ground is clay. On the 4<sup>th</sup> level the ground is calcareous. Other factors have influence on displacement increase and it is difficult to specify which ones influence more. Therefore, displacements could increase keeping free span constant or even reducing it.

### 5.3. ANCHORS POSITION DEVIATIONS INFLUENCE ON STRUCTURE HORIZONTAL DISPLACEMENTS

As referred before, anchors positioning suffered some deviations, especially on BC front. To measure the influence of this situation on wall displacements, two models were settled on finite element method software: Plaxis 2D. Soil parameters used are presented in Table 1. The first model – *MP* – has the anchors located as predicted on the design. The second model - *Alt 1* – has the anchors insertion point at about 80% of the respective levels height. The horizontal displacements were measured at each construction phase on 4 different wall points. The results are on Figure 4.

It is observed that the horizontal displacements reach higher values on model *Alt 1* when compared with *MP*. Looking to the average values, only in point D displacements in both models tend to be equal. In accordance with Table 4, on points A and B displacement increase is clearer on tensioning phases (P4 and P6). Instead, the larger displacement increments on two last levels happened on C and D measuring points, on excavation phases (P7 and P9).

**Table 4 - Horizontal wall displacements on both models by execution phase. Note: i) red phases indicate excavation and green phases indicate tensioning ii) the values on parenthesis correspond to the variation, in percentage, between the current phase and the one before**

Phase	A		B		C		D	
	MP	Alt 1	MP	Alt 1	MP	Alt 1	MP	Alt 1
<b>P3</b>	1	1	2	2	1,2	1	1,5	2
<b>P4</b>	-7 (800%)	-11 (1200%)	-3,5 (550%)	-3 (500%)	0,1	0,5	1,3	1,1
<b>P5</b>	-6,5	-11	-2,5	-2,1	0,1	1,1	2	1,6
<b>P6</b>	-8 (23%)	-14 (30%)	-3,5 (40%)	-5,6 (167%)	-2	-0,3	1	1,5
<b>P7</b>	-9	-14	-3	-4,8	1 (300%)	2 (200%)	2 (100%)	1,8 (20%)
<b>P8</b>	-9	-15	-4	-5,6	-1	-2	2	1,9
<b>P9</b>	-5	-11	-1,3	-1,5	4,5 (550%)	5 (700%)	7,3 (365%)	8 (420%)
<b>P10</b>	-5	-11	-1	-2	4	4,5	5,6	6,5
<b>Average Alt 1 / MP</b>	1,8		1,3		1,6		1,1	

The fact that *MP* displacements are 80% bigger than *Alt 1* displacements on point A and 30% on point B is justified with the wrong distribution of stresses that provides excess of stress on the top of the sustained soil. In fact, the *Alt 1* model shows higher displacements due to its unbalanced stress distribution.

### 5.4. WALL OVER-THICKNESS INFLUENCE ON STRUCTURE VERTICAL DISPLACEMENTS

On FG front, wall over-thickness was detected, being the average wall thickness about 53cm. It is now described the comparison made between two models designed on Plaxis 2D software.

The first one – *MP* – has 40 cm of wall thickness, as predicted on the design. The second one, *MS*, has 55 cm of wall thickness.

The maximum vertical displacement measured on model *MP* was 3.6 mm. As for *MS* model, the maximum displacement measured was 4.2mm. This difference is not considerable enough to conclude that wall thickness increase has influence on walls displacements. So, for now, this over thickness of 38% seems not to affect walls displacements.

## 5.5. BENCH WIDTH INFLUENCE ON STRUCTURE HORIZONTAL DISPLACEMENTS

In order to test the influence of bench volumes on minimizing walls displacements, three 3D models (A, B and C) were developed, with the help of *PLAXIS 3D* software. Soil parameters were settled as presented on Table 1. All the models followed BC front geological profile and geometry. Model A benches have dimensions similar to the ones suggested on the Design. In turn, model B was developed with benches dimensions measured on site. At last, model C has benches with dimensions that are approximately half of site benches.

The same excavations phases were defined for each model. Then, point C displacement was measured in every phase for all the three models. Point C was located approximately on the middle of the analyzed region. The displacements evolution of all three models is presented on Figure 9 graphic. It is observed that Model C, having narrower benches is the one that reaches higher displacements: 15,7mm. This value is 10% higher than the displacement reached by model B: 14,3mm. At last, model C reached 11,3 mm, which is 20% lower than B models displacement. It is verified that benches volume affects the formation of the arch effect.

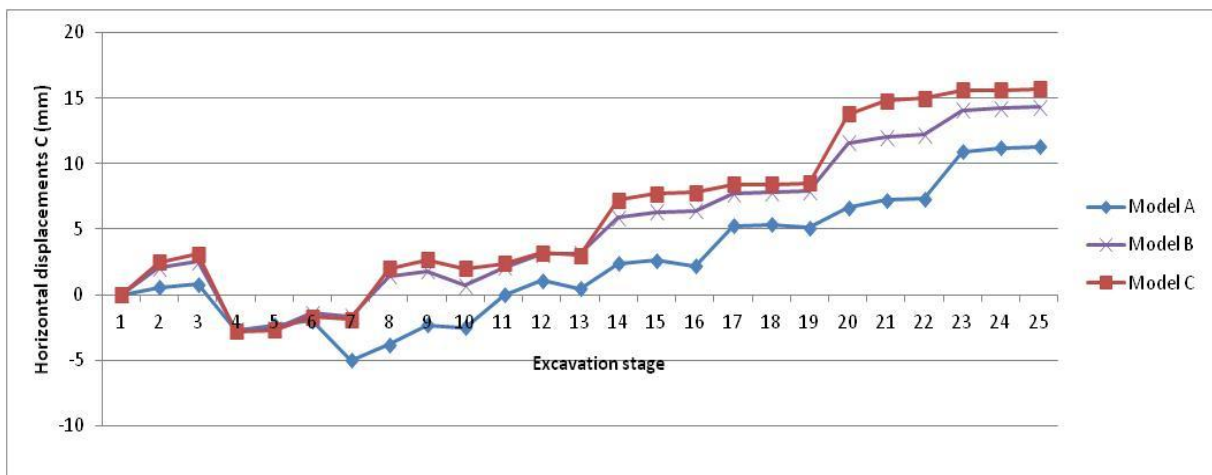
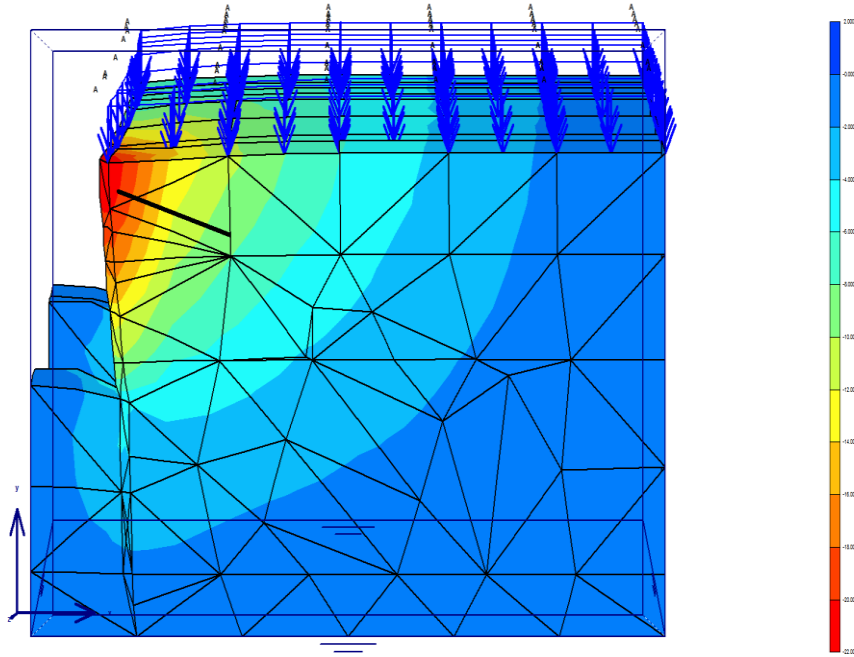


Figure 9 – Point C horizontal displacements evolution on the different models considered.

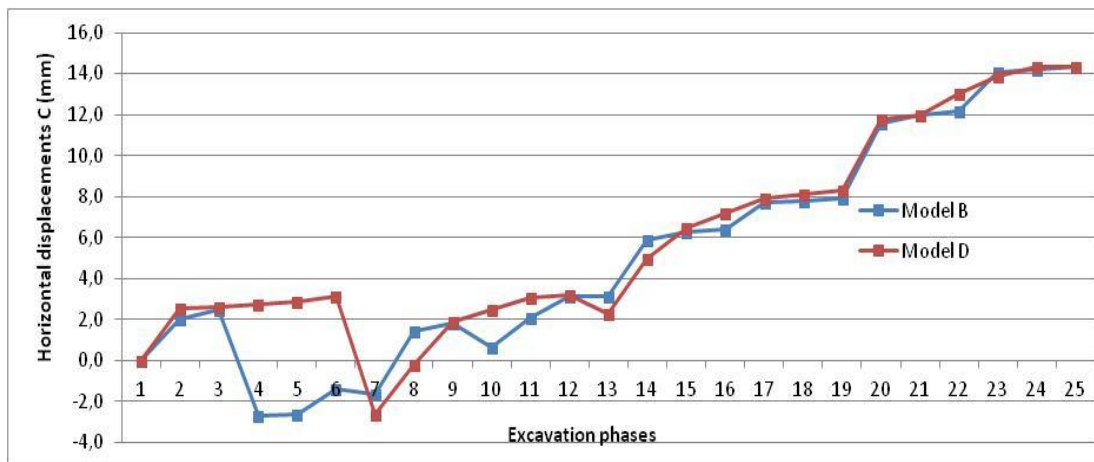


**Figure 10 – 3D horizontal displacements after the excavation of 4th level primary panel.**

In Figure 10 it is shown the horizontal displacements of model B after the excavation of 4<sup>th</sup> level primary panel.

## 5.6. PRIMARY PANELS LATE TENSIONING INFLUENCE ON STRUCTURE HORIZONTAL DISPLACEMENTS

In order to understand the effects on wall displacements of tensioning primary and secondary panels at the same time, model B from last modeling was used. However, the construction phasing was changed. Primary panel tensioning was moved to the phase where secondary panels are tensioned – model D. Figure 11 shows the horizontal displacements evolution in both models.



**Figure 11 – Point C horizontal displacements evolution on models B and D.**



Observing Figure 11, it is verified that the absolute displacement is the same on both models. However, displacements evolution on model D is different. On the first two levels, it is clear that displacements are higher on model D. The effects of tensioning primary panels at the exact moment (phase 3-4; 9-10) are only felt on the first levels of excavation.

## **6. CONCLUSIONS**

This work aimed at doing a quality control of a Berlin type wall execution in Lisbon. More than 40 visits to the site during the excavation were made..

It was noticed that the monitoring system installed had failures: it did not start at the same day that the retaining wall started to be executed and, in some fronts, the axis referential used was not the most correct.

Some of the design deviations identified could not be directly related to the displacements measured. It is believed that the influence is not detectable due to the low significance of those punctual situations. In some other deviations detected, after analyzing wall displacements, direct influence was detected. Those are the cases of: i) excavation of wider panels and ii) steel section removal.

The decision of increasing panel excavation width on the last levels is an example of the observational method application on site. It was a decision made in cooperation with the design responsible and was based on the better soil conditions found and also on the safe results given by the monitoring system.

It was observed, after the whole displacements analysis, that under no circumstances did the displacements absolute values approached the limits settled. The maximum displacement measured was nearly 10mm on FG front.

It was verified that relative displacements between phases grow with the increase of the ratio between soil pressure resulting force and benches resistant force.

At the same time, it was observed an increase of horizontal displacements with the free span between benches growth. However, there are another factors involved that can influence displacements.

It was verified that, changing anchors insertion point to a height of 80% of levels height, increases displacements in about 40%, on average.

According to the results obtained, it was observed that an over-thickness of 38% does not influence, on an evident way, wall displacements.



In accordance with the 3D analyses results, under these conditions, reducing bench volumes to about half, affects the arch effect formation and may increase displacements in 10%.

In excavations of this type, where superficial soil layers are more deformable, it must be guaranteed the exact time tensioning of primary panels.

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