Effect of pile driving on quay wall movement: a case study

Extended Abstract

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ABSTRACT

Driving piles into soft deposits can result in two major effects: besides heave, lateral soil displacements should be considered due to the influence on the integrity of already installed infrastructures. In this dissertation, the data regarding a Case Study of a quay wall that presented an abnormal deviation after the installation of a set of bearing piles in its active side was considered to develop a sensitivity analysis on the reliability of two analytical approaches: Cavity Expansion Method (CEM) and Shallow Strain-Path Method (SSPM). The analytical approaches allowed the estimation of the contribution of each bearing pile row to the movement of the quay wall; this estimation was used as calibration tool to develop a 2D finite element analysis (FEA) to module the bearing pile installation process, which was done by applying a volume expansion in each bearing pile row to match the correspondent estimation done by the analytical approaches. The FEA was developed considering information regarding the construction sequence and the soil parameters. It was concluded that both analytical approaches enable fair estimations on lateral displacements at small distances. However, in far-field conditions, the results are clearly overestimated, particularly through the CEM. The CEM also overestimates the volume expansion values obtained in the FEA for each row in the order of 50%-70%. The FEA analysis also enabled the conclusion that the construction process should have been different. Further investigation should be carried regarding the plugging effect, which was detected in the bearing piles, and 3D driven pile installation.

Keywords

Driven pile installation; Retaining wall deviation; Lateral soil displacements; Cavity Expansion Method; Shallow Strain-Path Method; Volume expansion of soil

1 INTRODUCTION

Driven piles are a cost-effective foundation solution for a lot of projects. Therefore, are commonly used as a foundation method in many countries with difficult ground conditions (Fleming *et al*, 2009) This dissertation considers an issue that was detected in a dock structure (quay wall): after installing the retaining wall dock structure, the soil on the active side of the wall was reinforced with the installation of a set of driven bearing piles (18 rows of 24 piles on a grid of 2.5 x 2.5 meters) in order to serve as the foundation solution to the heavy duty working platform behind the quay wall. Despite reports relating to the Case Study stating that the works were properly monitored, when preparing to cast the final section of heavy duty pavement on the five rows of piles immediately behind the quay wall, a movement of about 350 mm in the out-of-plane direction of the wall was verified. The problem was analysed by the project designers in different points of view, but the issue did not seem immediate to identify. However, the installation of the bearing piles started to be analysed more carefully due to potentially inducing lateral displacements in the retaining wall. This topic was analysed considering two different methodologies: the use of analytical approaches in order to understand if they could be considered as pertinent estimation tools to this type of movements and the consideration of a finite element analysis which used the available information on the reports to be undertaken (in terms of geotechnical information and construction sequence) and the analytical approaches as calibration tools for modelling process of the bearing pile installation. PLAXIS 2D was used for this study and it is a two-dimensional (2D) small-strain finite element formulation. In general terms, this dissertation considers the measured values of a specific Case Study in order to develop a sensitivity analysis on the reliability of the considered analytical approaches to estimate lateral displacements.

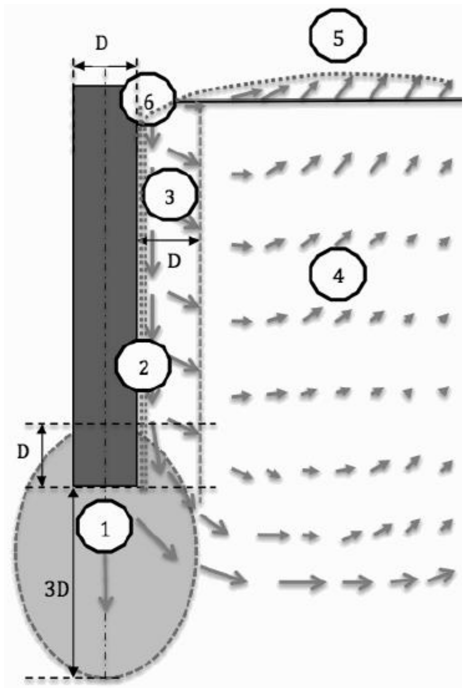
2 DRIVEN PILES INSTALLATION EFFECTS

Throughout the years, it has been possible to record several observations of ground and pile heave. The displacement mechanism regarding this phenomenon can result in several impacts, not only in the surrounding soil, but also in its already installed structures. The driven pile installation process leads to heave of the ground surface and, as a consequence, the generated upward forces induce a similar movement in the installed piles nearby (Massarsch & Wersall, 2013). When the buoyant force on the pile by remoulded clay exceeds the weight of the pile, the pile will float and can be squeezed out of the ground during the driving of adjacent piles (Massarsch, 1976). Lateral movements of the ground during pile installation are often neglected since they are difficult to detect. However, this effect becomes obvious when adjacent piles are displaced laterally. In Figure 1, six areas have been identified in order to describe the qualitative displacement field and soil disturbance caused by penetration of a single pile into soft clay (Massarsch & Wersall, 2013): According to Randolph *et al* (1979b), it was possible to conclude that, despite the early movement approximating to a spherical cavity expansion, the total radial stress change may be estimated based on modelling pile installation. Randolph *et al* (1979a) assumed that the expansion of the cavity takes place in a homogeneous, isotropic, ideal elastoplastic material, at initially isotropic stresses, using the theory of cylindrical cavity expansion to investigate the deformation pattern around a driven pile and, therefore, estimate the lateral displacement due to its installation, thus originating the Cavity Expansion Method (CEM). To consider the influence of the stress-free ground surface, Sagaseta *et al* (1997) modified the Strain-Path Method (SPM) to predict soil movement when the pile tip is not far below the soil surface, thus obtaining the Shallow Strain-Path Method (SSPM). as the expansion of a cylindrical cavity. The practical application of both methods relies on the following equations:

CEM: $$\frac{u}{R_0} = \left[\left(\frac{X}{R_0}\right)^2 + \rho\right]^{0,5} - \frac{X}{R_0} \quad (2\text{-}1)$$

SSPM: $$\delta_{r,SS}(r,0) = \frac{R^2}{2}\cdot\frac{L}{r\sqrt{r^2+L^2}} = \frac{\Omega}{2\pi}\cdot\frac{L}{r\sqrt{r^2+L^2}} \quad (2\text{-}2)$$

In which X and r are the distance from the pile shaft, R_0 and R are the pile radius, L is the pile length and ρ is the ratio of net pile area to gross pile area. u and $\delta_{r,SS}$ are the horizontal displacement.



1. Zone of disturbance below the pile toe: a bulb with high pressure created at the pile toe during driving accompanies the downward pile movement as it penetrates the ground;
2. Smear zone along the pile: the soil structure in this zone is almost destroyed and its width is very thin;
3. Zone of disturbance adjacent to the pile shaft: this disturbance is caused by the progressive downward movement of the pressurized bulb at the pile toe and not by the pile shaft;
4. Displacement configuration next to the disturbance area: during pile penetration, this area is exposed to resistance caused by passive earth pressure, due to the expansion of the pressure bulb of zone (1);
5. Displacement at ground surface: heave of the ground surface resulting from pile driving is small near the pile and reaches a maximum at about 0.3 to 1.0 times the pile length from the pile shaft;
6. Gap between the pile shaft and the surrounding soil: this gap and/or depression is the result of the downward movement of the pile toe during the initial phase of driving.

Figure 1 – Displacement field and disturbance zones during pile installation (adapted from Massarsch & Wersall, 2013)

3 ANALYSIS OF INSTALLATION EFFECTS

Randolph *et al*, 1979b developed the measurement of soil displacements on a diametric plane of a driven pile achieved by splitting a cylindrical sample of clay, thus generating a semi-circular prism of clay. The flat surface of the sample was then inscribed with a grid of lines before being covered by a perspex plate. After this procedure, a pile (also split longitudinally) was driven into the clay, flush with the perspex plate and the deformation analysis was undertaken by photographing the grid of distorted lines. This procedure was done for open and close-ended piles and it was possible to conclude a good agreement between the measured and predicted values.

Sagaseta & Whittle (2001) compared measurements with theoretical predictions from the SSPM analyses. Some measurements were carried out by Gue (1984) from driving close and open-ended (area ratio of 34%) steel piles into a cylindrical chamber with a diameter and depth of 450 mm filled with speswhite kaolin, prepared from a slurry under consolidation pressures from 200 kPa to 600 kPa and over-consolidation ratios from 1 to 10.

All of the piles had an outside diameter of 16 mm and were driven by hammering to a total depth of 344 mm (L/R = 43). It was possible to verify a very good agreement between measured and computed values. Both methods were also computed in the same geometry so that they could be compared. It was possible to conclude that both methods offered similar results at close distances (**Erro! A origem da referência não foi encontrada.** and Table 1).

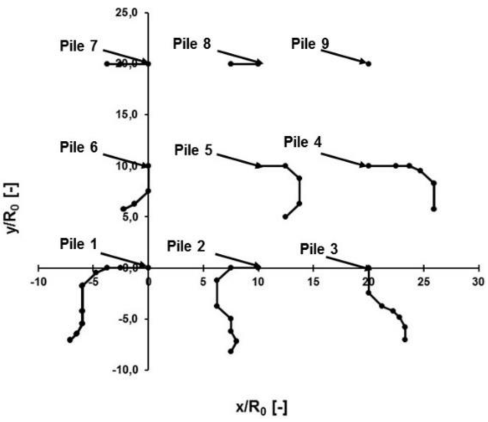


Figure 2 – Lateral displacements of pile group

Table 1 – CEM and SSPM comparison applied to pile group

Pile Id.\Displ.	CEM		SSPM	
	x [mm]	y [mm]	x [mm]	y [mm]
Pile 1	21.35	21.35	21.19	21.19
Pile 2	7.48	24.72	7.48	24.56
Pile 3	10.12	21.35	10.00	21.19
Pile 4	17.97	12.73	17.88	12.69
Pile 5	7.48	14.97	7.48	14.94
Pile 6	6.74	12.73	6.69	12.69
Pile 7	11.23	0.00	11.19	0.00
Pile 8	7.48	0.00	7.48	0.00
Pile 9	0.00	0.00	0.00	0.00

4 CASE-STUDY

The Case Study is based on a heavy-duty quay for the load-in of marine structures. The dock structure comprises a steel combi-pile wall (Figure 3) with a piled load bearing slab behind.

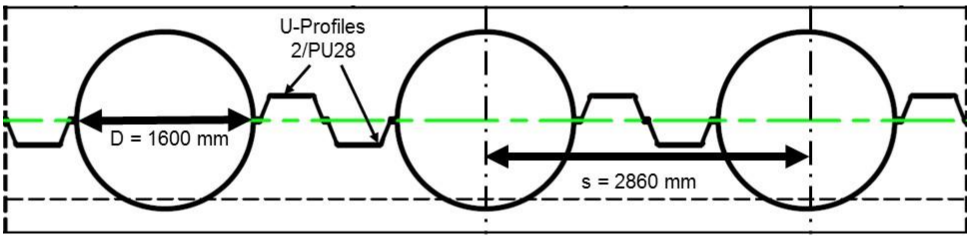


Figure 3 – Scheme of wall section (only for the "Quay Wall")

The construction sequence developed in the Case Study is considered in the following description:

1. Drive 1600 mm diameter and 20 mm thickness combi-pile wall through glacial till to sandstone at about 22 m depth;
2. Backfill behind wall to allow access to tube heads and then ream-out tubes, form a 3-4 m rock socket and infill with reinforced concrete;
3. Install 660 mm diameter and 14 mm thickness steel tube bearing piles on 2.5 x 2.5 m grid behind quay wall: photographic evidence suggests that bearing pile installation actually started at about the same time as the wall piling, and that all but the last five rows immediately behind the wall (left out to allow access to the wall), were completed;
4. Install tiebacks and cast heavy duty pavement slab on bearing piles: at this stage, a horizontal movement of the retaining wall piles of up to 350 mm was identified. When this happened, the remaining 5 rows of bearing piles had been driven behind the combi-wall;
5. Remove berm to dry dock level: naturally, this stage was delayed while the reasons for the movement were examined and remedial measures were developed.

It was concluded that the installation of the bearing piles had to be considered the main cause. Taking into account the analytical approaches already described, it was possible to calculate the contribution of each first five rows of bearing piles to the movement of the retaining wall (Table 2).

Table 2 - Minimum, average and maximum values of the contribution of each row of bearing piles to the movement of the retaining wall in both methodologies (CEM and SSPM)

Rows	Minimum		Average		Maximum	
	CEM	SSPM	CEM	SSPM	CEM	SSPM
1st row	22.29%	23.76%	23.37%	24.98%	25.28%	27.26%
2nd row	20.75%	21.57%	21.33%	22.05%	21.69%	22.48%
3rd row	19.16%	18.99%	19.72%	19.60%	19.98%	19.87%
4th row	17.62%	16.67%	18.37%	17.59%	18.83%	18.11%
5th row	16.47%	14.79%	17.20%	15.78%	17.73%	16.39%

In Table 3 is presented the description of the profile that was considered to analyse the design conditions, considering the available information in the reports. It should be noted that the natural groundwater level is considered to be at the elevation of -0.65 meters in terms of initial conditions of the model.

Table 3 – Initial geometry of the ground profile considered in the original design

Stratum no.	Elevation of top of stratum (m)	Soil Types	
		Active Side	Passive Side
1	5.90	Granular Fill	Granular Fill
2	0.00	Reworked Clay	Reworked Clay
3	-6.65	Firm to Stiff Clay	Firm to Stiff Clay
4	-12.65	Sand	Sand
3	-16.65	Firm to Stiff Clay	Firm to Stiff Clay
5	-22.60	Sandstone	Sandstone

By means of a finite element mesh that was particularly refined in the area surrounding the bearing pile and berm locations, a scheme of calculation phases was developed. The calculation stopped at final stage of the berm excavation due to a “soil body collapse”. In Figure 4 is presented the output of model at the corresponding phase. Right below the berm excavation a region of plastic points is developed that seems to be related to the formation of a collapse mechanism. In this region, the water table is at the level of the base of the berm, which can generate a resistance problem on the stratum below the berm since the respective effective stresses will be significantly low. Site investigation information obtained after the wall misalignment was discovered was used to review the interpreted soil and rock stratification and the geotechnical properties of the various strata (Table 4). After generating the initial conditions, the model is developed according to the construction sequence that was deduced from the technical reports. However, due to the alterations in these models in terms of geometry and materials, it was possible to account for the rest of the stages. In these cases, it was possible to reproduce the effect of bearing pile installation, which considered the following steps:

1) Vertical lines of solid elements were included in the mesh at the location of each row of driven bearing piles;
2) At each cluster of elements representing a row of piles, an internal volume expansion was applied to create a cavity expansion effect within the mesh. Each row was treated in this manner in the order of installation reported with the amount of volume expansion calibrated to produce with the overall recorded combi-wall movement.

This process was developed based on the analytical calculations through the CEM and SSPM applied to this Case Study. In Table 5 is a summary that displays the differences between both the analytical and numerical approaches. After imposing the necessary volume strain in each bearing pile row, the material of the same clusters is updated from soil to the bearing pile material.

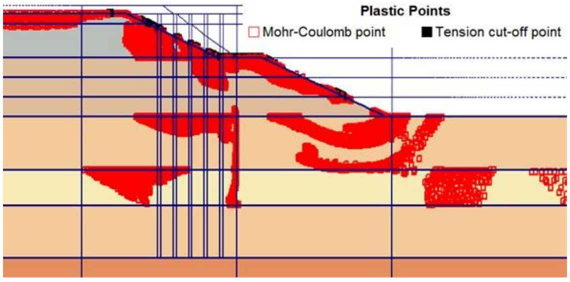


Figure 4 – Plastic points location obtained from the output of the design model

Table 4 – Initial geometry of the ground profile for the revised models

Stratum no.	Top of stratum level (m)	Soil Types	
		Active Side	Passive Side
1	5.90	Granular Fill	Granular Fill
2	0.00	Clayey Fill	Clayey Fill
3	-6.65	Till-Clay	Till-Clay
4	-15.40	Till-Granular	Till-Granular
5	-23.60	Sandstone	Sandstone

Other models were also developed considering some differences. For instance, the clayey materials were also analysed taking into account an undrained behaviour. In terms modelling sequence, these undrained models did not present differences when compared to the Revised Drained Model.

Table 5 – Comparison between the required contribution of each bearing pile row to produce a similar displacement in the retaining wall

Rows	Cavity Expansion Method		Finite Element Analysis	
	Percentage [%]	Displacement [mm]	Percentage [%]	Displacement [mm]
1st row	25.28%	87.71	16.00%	86.80
2nd row	21.69%	75.28	13.00%	74.80
3rd row	19.98%	69.33	11.50%	70.59
4th row	18.83%	65.33	11.50%	64.93
5th row	17.73%	61.51	11.75%	61.20

However, in order to match the same level of displacements achieved, it was necessary to apply a significantly larger volume expansion value (Table 6). Considering the same geometry, materials, interfaces, meshing, boundary and initial conditions as the ones presented in the "Revised Drained Model", it was developed a model with a difference on the construction sequence: installation of an anchor before driving the bearing piles (Table 7).

Table 6 – Comparison between the volume expansion values that will be necessary in the "Modified Undrained Model" to achieve the same level of displacements obtained in the "Drained Model"

Rows	Drained Model		Modified Undrained Model	
	Volume Expansion [%]	Maximum Displacement [mm]	Volume Expansion [%]	Maximum Displacement [mm]
1st row	16.00%	86.80	25.00%	81.92
2nd row	13.00%	74.80	21.00%	75.35
3rd row	11.50%	70.59	18.00%	68.33
4th row	11.50%	64.93	15.00%	65.26
5th row	11.75%	61.20	12.50%	62.28

The numerical results considered two different moments in the analysis applied in five different models, described in Table 8: immediately after the installation of the five rows of bearing piles, in order to replicate the "design concept", and after final excavation of the berm in the passive side of the retaining wall. Considering Figure 5, comparing to the values already obtained immediately after bearing pile installation, the final excavation (in average) contributed to increase the out-of-plane deviation in approximately 9%, the shear forces in 17% and the bending moments in 77%. In Table 9 is presented the final configuration of the numerical results immediately after bearing pile installation and after excavation of the berm.

Table 7 – Comparison of the of the contribution of each bearing pile row to the maximum and at the pile head movements between the "Revised Drained Model" and the "Anchored Revised Model" for the same values of volume expansion

Rows	Volume Expansion [%]	Maximum Displacement [mm]			
		Revised Drained Model		Anchored Revised Model	
		At Pile Head	Maximum	At Pile Head	Maximum
1^{st} row	16.00%	86.80		13.52	51.89
2^{nd} row	13.00%	74.80		9.30	36.29
3^{rd} row	11.50%	70.59		8.08	27.53
4^{th} row	11.50%	64.93		7.93	24.32
5^{th} row	11.75%	61.20		7.87	22.98
	Total	358.32		46.7	163.01

It is evident that the anchor forces before the final excavation will be significantly larger in Model C due to the activation of the anchors before the bearing pile installation, which means that the presented value will be the cumulated result of the simulation of the installation of five rows of bearing piles.

Table 8 – Legend indicating the model designators being considered

A1	Revised Drained Model without Bearing Piles
A2	Revised Drained Model with Bearing Piles
B1	Revised Undrained Model with Bearing Piles
B2	Modified Undrained Model with Bearing Piles
C	Pre-Anchored Revised (Drained) Model with Bearing Piles

Table 9 – Anchor forces (kN/m) developed in the tiebacks before and after the excavation of the berm in the passive side of the retaining wall

Model	A1	A2	B1	B2	C
Bearing piles modelled [-]	No	Yes	Yes	Yes	Yes
Before Final Excavation [kN/m]	21.6	16.6	47.1	54.6	1201
After Final Excavation [kN/m]	447	440	444	493	1487
Effect of Final Excavation [kN/m]	+425	+423	+397	+438	+286

It is clear increase in the out-of-plane deviation, shear forces, bending moments and anchor forces. However, in relative terms, comparing to the values already obtained immediately after bearing pile installation, the final excavation (in average) contributed to increase the out-of-plane deviation in approximately 9%, the shear forces in 17% and the bending moments in 77%. The difference in the bending moments is mainly due to the more accentuated increase in model A2. In terms of anchor forces, in models A1, A2, B1 and B2 the effect of final excavation is significant due to the construction sequence already mentioned in these cases. However, in model C the relative impact is significantly reduced. This analysis may lead to believe that the final excavation of the berm would not have impacted that much the works (at least, in terms of deviation, which seemed to be the issue). The difference in the bending moments is mainly due to the more accentuated increase in model A2. In terms of anchor forces, in models A1, A2, B1 and B2 the effect of final excavation is significant due to the construction sequence already mentioned in these cases. However, in model C the relative impact is significantly reduced. This analysis may lead to believe that the final excavation of the berm would not have impacted that much the works (at least, in terms of deviation, which seemed to be the issue).

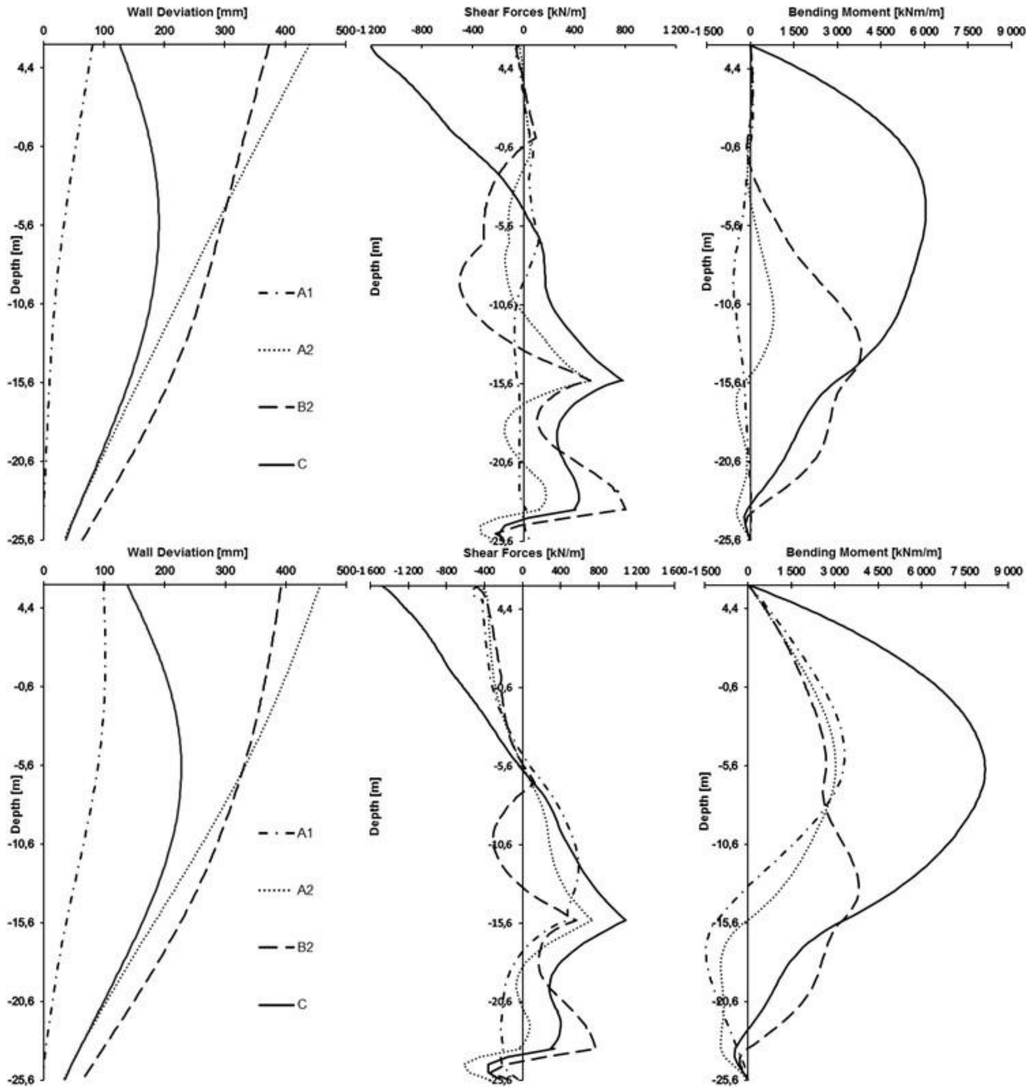


Figure 5 – Numerical results (above – immediately after bearing pile installation; below – after excavation of the berm)

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

CEM and SSPM enable similar estimations on the lateral displacements due to pile driving when the distance between the installed driven pile(s) and the target being considered to estimate its subsequent deviation is within 5-10 pile radii. However, the difference between both approaches in terms of the contribution to the movement of the retaining wall accentuates in far-field conditions. The far-field analysis is usually underappreciated in comparison with the influence of lateral displacements on adjacent piles. In order to develop a more suitable estimation of driven pile installation in the far-field regions, it could be pertinent to consider small scale tests to analyse this issue with more detail and the incorporation of nonlinear stiffness in an analytical approach similar to CEM and in a large strain numerical model. Taking into account the values presented in Table 5, it was possible to verify that, for this geometry, the CEM overestimates the "real" contribution of each bearing pile row to the movement of the retaining wall in the order of 50% to 70%. It should be noted that the construction sequence in Model C (Table 8) could have been considered in order to mitigate the abnormal values of out-of-plane deviation (despite the significantly higher values in terms of shear forces, bending moments and anchor forces). Regarding the effects of plug on horizontal displacements due to pile driving it is important to note that Randolph *et al* (1979b) reached the analytical conclusions regarding plugging in experimental cases in which the ratio between the pile diameter and its correspondent thickness was particularly small ($Dt/=81.6/=5$). Most real cases of open-ended piles are characterized by much larger values for that ratio (in this Case Study, $Dt/=66014.8/\cong 45$). Randolph *et al* (1979b) suggest that the plugging effect on open-ended piles will continually change the displacement field with depth, which means that the analysis process of soil displacement paths for open-ended piles and for close-ended piles will vary significantly. The relation between the open-ended pile diameter and the thickness of the respective walls should be analysed more consistently in order to understand the influence of that relation in the differences between the effects generated due to driven pile installation. For cases in which the inner diameter is smaller, it is likely that the plugging effect could be developed earlier in terms of the pile installation process, thus enabling the behaviour as close-ended pile throughout a larger length (which would benefit the pile in terms of its capacity, but also lead to higher disturbances in its surroundings). For cases in which the inner diameter of the driven pile is larger, since the soil mass within the pile is greater, the inner friction needed to mobilise the plug would have to be higher. It is also suggested a 3D analysis in order to reproduce the pile installation process in a more realistic way since this volume expansion problem is actually more prone to be axisymmetric form instead of a plane strain issue.

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