Critical analysis on the foundation of a new distribution centre in Castanheira do Ribatejo

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Abstract

The foundation solution for a new distribution centre in Castanheira do Ribatejo was analysed. The solution is split in two parts, the one for the main buildings and the one for the outer areas of the project. Both of these are looked into on a theoretical scale and are verified by calculations were possible. They are put against the specific parameters of the project and the models for calculation are explained. A column supported embankment is needed for the main warehouse building as settlement of the soil and seismic activity are the main challenges of the area. The outer areas are improved with vibro compacted stone columns as the margin on settlements is bigger but long term secondary settlements still pose a problem. The combination of these columns with a preload embankment eliminates most of the secondary settlements in a span of eight months. Lastly, these solutions are put against ideas proposed by the student in a technical and economical comparison. For the first solution, it was found that there a several alternatives for the indirect pile foundation like driven cast in place piles, Atlas screw piles, Omega screw piles and even Franki piles. Their true viability as an option needs to be tested further in the project parameters to make an calculated decision. For the second solution, an alternative was found in ground improvement with prefabricated vertical drains. It was found that these, while being better in terms of cost, were not the optimal choice as the stone columns have the double use of settlement control and the ability to carry loads.

Keywords: Column supported embankment, vibro compacted stone columns, settlements, soft soil layers, theoretical analysis, technical and economical comparison.

1. Introduction

The alluvial plains near the Tagus river in Portugal provide engineering challenges for big industrial projects. The top soil layers of these plains have very low mechanical qualities and with competent soil layers at depths of 20 to 30 meters, the demand for deep foundations arises. This combined with the problem of secondary settlements during exploitation and seismic activity makes an interesting case.

The project described here is the foundation work for a new distribution centre in Castanheira do Ribatejo. The project is owned by Jerómino Martins and the research into the foundation solution and implementation is done by CêGê and JETsj. These companies have proposed two solutions for the project, one for the main buildings and one for the outside areas and access ways. Since any secondary settlements have to minimized for the main buildings, a column supported embankment was proposed. With this method the soil is reinforced with piles and the loads of the building are transferred to these piles through an embankment. In the outside areas of the project, a solution of ground improvement through vibro compacted stone columns combined with a preload embankment was proposed. This combination is used to accelerate consolidation and almost eliminate any secondary settlements that would occur long term.

2. Introduction of the construction site

The entire project covers a total area of 149.810 m² and contains the construction of an industrial warehouse with a covered area of approximately 72.230 m². Apart from the warehouse, several support buildings like a nursery and a silo for car parking will be erected as well. Each of the buildings will have their own solution in terms of foundation.

3. Main geological conditions

The project area is on the right bank of the river Tagus which is primarily dominated by alluviums, ancient deposits of river terraces and bedrock dating back to the Miocene. The presence of the alluvial layers in the soil, with a thickness varying between 30 and 33 m in the area of the project, and seismic activity provides a challenge from an engineering standpoint to create durable and safe foundation solutions.

4. Proposed solution for the main warehouse

The solution proposed for the main warehouse of the project is a column supported embankment (CSE) to keep settlements of the area within acceptable ranges. The main superstructure of the warehouse is supported by foundation masses with one, two or four piles.

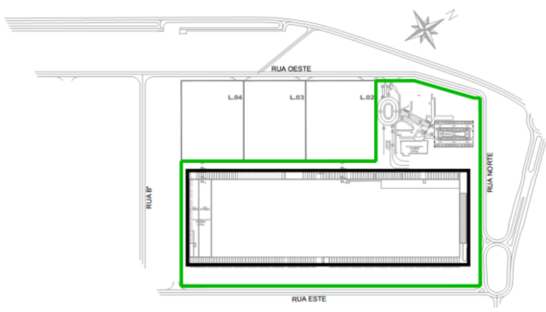

Figure 1: Location of the main warehouse (black outline) in the project area (green outline)

5. Column supported embankments (CSE)

According to Collin, et al. (2005), Column supported embankments consist of vertical columns that are designed to transfer the load of an embankment through a compressible soil layer to a firm foundation. The selection of the columns used depends on the design loads, constructability, cost, etc.

In order to minimize the number of columns needed and to increase the efficiency of the design, a geosynthetically reinforced Load Transfer Platform (LTP) can be used. (Collin, Han, & Huang, 2005).

6. Foundation piles for the CSE

The proposed columns are driven precast piles in reinforced concrete. These piles will have a square section of 400 mm x 400 mm and will be placed in a grid of 3.95 m by 3.45 m with the pile-driving process. These piles have a finite length due to handling and transport from the factory to the construction site. Since stable soil layers can only be found at great depths of around 30 m, the need for a joint between several piles arises. The joining of the piles is performed with ABB type joints and will ensure the continuity of the characteristics of the piles.

Table 1: Parameters of the concrete piles

Section	Steel	Concrete	As (cm²)	d (m)	Nrd (kN)	Mrd (kN)
0,4 m x 0,4 m	A500 NR SD fyd = 453 Mpa	C50/60 fcd = 33 Mpa	8Ø25 39,27 cm²	0,35	6859	205

7. Earthworks

In order to guarantee the necessary conditions for movement of equipment and safety, a working platform will be set up with a thickness of 0.50 m. The platform will be set up between the heights of +2.0 m and +2.5 m and will consist of aggregates with a granulometry between 15 and 40 mm reinforced with a geotextile.

To make sure the loads are transferred to the piles and not to the soil in between, pile caps of reinforced concrete at the base of this work platform (+2.50 m) will be used. They will have a square geometry of 1.80 x 1.80 m and a thickness of 0.50 m.

On top of this, the presented solution proposes a load transfer platform between +3.0 m (+2.50 m + the thickness of the pile caps of 0.50 m) and 5.60 m, resulting in a total height of 2.60 m.

The floor slab itself will have a thickness of 0.20 m and will be constructed between +5.60 m and +5.80 m. The entire solution is designed to accommodate an overload of 60 kN/m² combined with the permanent loads of the embankment and the concrete slab.

Table 2: Earthworks per layer

Layer	Materials	Base height (m)	Top height (m)	Total height (m)
Warehouse floor	Reinforced concrete slab	5,60	5,80	0,20
Permanent landfill	Compacted Tout-venant	2,50	5,60	3,10
	Geotextile			
Work platform	Aggregates with an extensive granulometry (15-40 mm)	2,00	2,50	0,50
	Geotextile			

8. Proposed solution of the supporting buildings

The foundation of the car silo, the nursery and the other support buildings will be characterized by a structural slab in reinforced concrete supported by foundation beams also in reinforced concrete. These beams will be supported by foundation masses receiving the loads of the floor slab and the pillars of the superstructure. As is the case for the warehouse, prefabricated piles of 400 x 400 mm will be used to reduce the risk of settlements of the soil. The difference with the main warehouse is that no embankment will be used to distribute and transfer the loads.

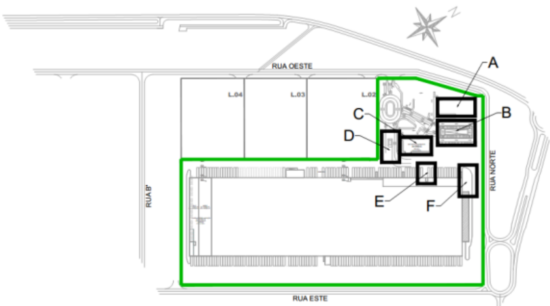

Figure 2: Location of the nursery (A), the car silo (B), the social building (C), the entrance way (D), the walkway (E) and the water reserves (F)

9. Proposed solution for the outer areas and access ways

The outdoor areas and access ways of the project will have a ground improvement through the implementation of stone columns with the vibro replacement technique. This solution in combination with a preload embankment aims to eliminate most of the secondary settlements of the terrain in the exploitation phase.

10. Vibro replacement

According to Sayar and Khalilpasha (2013), vibro replacement is a technique that builds load-bearing columns made from gravel or crushed aggregates in cohesive soils and granular soils with a high amount of fine materials. This technique falls into the category of deep vibratory compaction techniques in which soft soils get improved for building purposes by using special depth vibrators. (Priebe, 1995).

11. Application in the project

The aim of this solution is to mitigate the settlements of alluvial formations of the outside areas of the project during the construction and exploitation phases. For this purpose a combination of stone columns and a preload landfill will be used. The stone columns improve the soil for load transfer with their high shear resistance and the preload landfill will accelerate the consolidation of the soil to enable control of the settlements. The combination of these two things allow for a homogenous character of deformation.

These stone columns will consist of vibro compacted gravel and will be placed in a grid of 2.80 m x 2.80 m. The average length of the columns will be 30 m with an average diameter of 0.95 m.

The preferred method to install these stone columns is the dry bottom feed crane-hung method since depths of 30 m have to reached.

12. Earthworks

The execution of these gravel columns require a stable work platform as heavy equipment will be necessary. As in the main warehouse solution, a work platform with a thickness of 0.50 m will be set up between the soil levels of +2.00 m and +2.50 m.

After the execution of the stone columns, the working platform will be cleaned and improved to remove any contaminants in general. On top of this cleaned layer, a drainage layer will be placed up until the level of +2.90 m. This layer will have an average thickness of 0.40 m and will consist of compacted gravel with a grain size between 15 and 70 mm. This entire layer will be wrapped in a geotextile of 220 g/m² and will ensure the free flow of water through the layer.

A definitive embankment up until +4.60 will be implemented for the outside areas. Taking the final height for the outside areas into account, an average height of 2.60 m of land will be needed for the embankments.

A temporary preload layer will be set up between levels of +4.60 m and +6.60 m for a total height of 2.00 m. This layer will help eliminate most secondary settlements in the long term. After conclusion of the consolidation process, this embankment will be removed while levelling the platform to +4.00 m. The construction of the pavement around the warehouse will take a height of about 0.60 m to get back to the level of +4.60 m.

Table 3: Summary of the needed earthworks

Layer	Materials	Base height (m)	Top height (m)	Total height (m)
Preload embankment	Compacted selected materials	4,60	6,60	2,00
Definitive embankment	Uncompacted selected materials	2,90	4,60	1,70
	Geotextile - 220 g/m²			
Drainage layer	Aggregates with an extensive granulometry (15-70 mm)	2,50	2,90	0,40
	Geotextile - 220 g/m²			
Work platform	Aggregates with an extensive granulometry (15-40 mm)	2,00	2,50	0,50
	Geotextile - 220 g/m²			

13. Other options for piles in CSE's

Firstly some alternative piles are given that are used in Portugal like prefabricated steel piles and driven cast in place piles. This is followed by several alternatives that aren't used in Portugal like Franki, Atlas and Omega piles. Even though there is a lack of experience with these piles, they are still worth considering. (Franki, Atlas screw pile, 2018) (Franki, Driven cast in place piles, 2018) (Franki, Franki pile, 2018) (Franki, Omega screw pile, 2018) (Etekch, 2010) (Beatty, 2018).

Table 4: Comparison of advantages of different pile solutions used in Portugal

	Prefabricated piles reinforced concrete	Prefabricated piles steel	Driven cast in place piles
ADVANTAGES	No spoils generated on site	No spoils generated on site	No spoils generated on site
	Speed of installation	Speed of installation	Pile length can be determined before casting and can easily be cut or extended
	Piling is unaffected by ground water level	Ready for immediate follow-on construction	The soil displacement causes compaction at the pile tip which increases bearing capacity
	Ready for immediate follow-on construction	Pile can be cut to desired length and extended through welding	Relatively inexpensive
	Pile can be cut to desired length	The soil displacement causes compaction at the pile tip which increases bearing capacity	Pile length can be adjusted to the situation
	Pile bearing capacity can be tested during implementation	Great strength combined with a small section	Reinforcement is not determined by handling and driving stresses
	The soil displacement causes compaction at the pile tip which increases bearing capacity		Full ground displacment
	The soil displacement causes increased friction which increases bearing capacity		
	Relatively inexpensive		

Table 5: Comparison of disadvantages of different pile solutions used in Portugal

	Prefabricated piles reinforced concrete	Prefabricated piles steel	Driven cast in place piles
DISADVANTAGES	Piles can get damaged during the driving process	Piles can get damaged during the driving process but the pile tip can be widened to reduce damage	Piles can get damaged after reclaiming of the casing due to necking or waisting because of high lateral forces in the soil
	Piles can get laterally displaced by obstructions in the ground	Piles can get laterally displaced by obstructions in the ground	Concrete cannot be inspected after completion
	Pile lenght is limited due to ease of handling and transport	Pile lenght is limited due to ease of handling and transport	Heavy equipment needed on site
	The use of joints is needed for greater depths	Heavy equipment needed on site	Installation causes noise and vibrations
	Heavy equipment needed on site	Installation causes noise and vibrations	The casing can get damaged during driving
	Installation causes noise and vibrations	Exact length is determined during installation which increases cost due to cutting or extending	Follow-on construction has to wait on the hardening of the concrete
	Reinforcement is determined by the effects of handling and driving stresses	Limited friction due to limited lateral soil displacement	
	Exact length is determined during installation which increases cost due to cutting or extending	Relative high cost of steel profiles	
		Susceptibility to corrosion	

Table 6: Comparison of advantages of different pile solutions not used in Portugal

	Franki piles	Atlas screw piles	Omega screw piles
ADVANTAGES	No spoils generated on site	Limited or no spoils generated on site	Limited or no spoils generated on site
	Pile length can be determined before casting and can easily be cut or extended	Very little effect on the environment	Very little effect on the environment
	The soil displacement causes compaction at the pile tip which increases bearing capacity	Double lateral soil displacement resulting in high bearing capacity	Double lateral soil displacement resulting in high bearing capacity
	The use of the wide end allows the pile to withstand very high tensile and compressive forces	Relatively easy and quick to install	Behaves like a soil displacement pile with high friction resistance
	Pile length can be adjusted to the situation	Pile length can be adjusted to the situation	Pile length can be adjusted to the situation
	Reinforcement is not determined by handling and driving stresses	Reinforcement is not determined by handling and driving stresses	Reinforcement is not determined by handling and driving stresses
	Low noise and vibrations due to the use of an internal hammer	Low noise and vibration-free	Low noise and vibration-free
	Full ground displacement	Suitable for all soil profiles	Suitable for all soil profiles
		Relatively inexpensive	Can be implemented in combination with simultaneous grout injections to increase penetration rate

Table 7: Comparison of disadvantages of different pile solutions not used in Portugal

	Franki piles	Atlas screw piles	Omega screw piles
DISADVANTAGES	Piles can get damaged after reclaiming of the casing due to necking or waisting because of high lateral forces in the soil	Piles are susceptible to necking or waisting because of high lateral forces in the soil	Piles are susceptible to necking or waisting because of high lateral forces in the soil
	Concrete cannot be inspected after completion	Concrete cannot be inspected after completion	Concrete cannot be inspected after completion
	Heavy equipment needed on site	Heavy equipment needed on site	Heavy equipment needed on site
	The casing can get damaged during driving	Follow-on construction has to wait on the hardening of the concrete	Follow-on construction has to wait on the hardening of the concrete
	Relatively expensive	Cost can vary because of unpredictable soil conditions	Cost can vary because of unpredictable soil conditions
	Follow-on construction has to wait on the hardening of the concrete		

14. Technical and economical comparison with the proposed solution

At first glance there seem to be clear winners in terms of cost compared to the proposed solution like the driven cast in place pile, the Atlas screw pile and the Omega screw pile. Even on a technical scale they provide significant advantages in comparison with driven precast piles.

These winners have some disadvantages as well for the current project. Firstly, the follow-on construction has to wait for the concrete to harden which implies more time lost when the construction schedule is tight. Secondly, the need for heavy equipment on site can add extra costs which may render the solutions not economically viable. Lastly, the concrete cannot be inspected after completion of the piles which is another downside to the ease of inspection of the precast concrete piles with a stress wave test.

The H-piles have similar advantages to the precast concrete piles in the sense that they are easily and quickly installed and that the follow-on construction can happen immediately. The main disadvantages here are the high cost of the steel profiles and their susceptibility to corrosion.

Franki piles are similar to the precast piles in terms of cost but they share the same advantages and disadvantages with the driven cast in place piles. The wide end of the pile can increase compression resistance and lead to a smaller diameter and a lower price.

In conclusion, it is found that there are several possible alternatives to the current solution of the project like driven cast in place piles, Atlas screw piles, Omega screw piles and even Franki piles. Their true viability can only be assessed when calculated in the situational parameters of the entire project. Further research is needed to choose an adequate alternative.

Table 8: Price comparison between the current solution and the proposed solutions

Pile type	Driven precast piles	Steel piles	Driven cast in place	Franki piles	Atlas screw piles	Omega screw piles
Total price	€ 16 977 600,00	€ 32 320 320,00	€ 5 659 200,00	€ 18 864 000,00	€ 10 139 400,00	€ 9 733 824,00
Total price per m²	€ 214,96	€ 409,22	€ 71,65	€ 238,84	€ 128,38	€ 123,24

15. Prefabricated vertical drains as another option for ground improvement of the outside areas

Another way of accelerating consolidation of the soil is improving it with Prefabricated Vertical Drains (PVD). These vertical drains, also called wick drains, are used to make soft compressible soils with low bearing capacity constructible. They consist of a plastic core encased by a geotextile and can accelerate the consolidation of the subsoil when used in combination with a preload embankment, giving the excess pore water a faster way to flow out of the soft soil layers (Cofra, 2015).

16. Technical comparison with the proposed solution

The proposed ground improvement technique is compared with the project solution on a scale of advantages and disadvantages. A small technical analysis in terms of consolidation time will be carried out as well (Raju, Krishna Hari, & Wegner, 2004) (Fox & Scorza, 2014) (Rixner, Kraemer, & Smith, 1986) (Cofra, 2015) (Sayar & Khalilpasha, 2013).

Table 9: Comparison of advantages of ground improvement methods

	Vibro replacement stone columns	Prefabricated vertical geodrains
ADVANTAGES	Improvement of the stiffness in the subsoil to decrease settlements.	A decrease in overall time for the completion of primary consolidation due to preloading
	Improvement in the shear strength of the subsoil to increase bearing capacity	A decrease in the amount of preload needed to achieve this consolidation
	Compaction of loose non-cohesive soils to mitigate liquification potential	An increase of the rate of strength gain of the soil due to consolidation
	Increase of the bearing capacity of the soil because the columns themselves can carry loads	Less disturbance to the soil mass than soil improvement techniques with soil displacement
	Rapid consolidation of the subsoil due to preloading	The speed and simplicity of installation
		Little disruption of the various soil layers

Table 10: Comparison of disadvantages of ground improvement methods

	Vibro replacement stone columns	Prefabricated vertical geodrains
DISADVANTAGES	Installation takes more time	The only increase in bearing capacity is because of rapid consolidation of the soil
	Does not work with all soil types so an extensive analysis into the soil is needed	Predrilling, jetting or the use of a vibratory hammer might be needed in dense soils or soils with a lot of obstructions
	Requires special equipment and expertise	Requires special equipment and expertise
	Disturbance to the soil mass which can be problematic in sensitive soils	Requires a preload embankment to have any effect

As a small technical comparison, the consolidation time to reach an average degree of consolidation of 90% will be compared between the two techniques. In this calculation, the same spacing as in the project will be used for the PVD's, 2.80x2.80 m.

For the stone columns the consolidation time was calculated to be eight months with the following formula:

$$T_h = \frac{C_h * t}{d_e^2} \quad (1)$$

Table 11: Parameters and calculated consolidation time for the stone columns

Ch (m²/s)	U	Th	Spacing L (m)	t (months)
2,80E-08	0,90	0,848	2,8	8

Table 12: Parameters used for the calculation of the PVD's (CeTeau, 2014)

Ch (m²/s)	Spacing L (m)	D (m)	d (m)	U	l (m)	kc (m/s)	qw (m³/s)
2,80E-08	2,8	3,164	0,05	0,9	30	3,35E-10	1,80E-04

The following simplified formula can be used to calculate the consolidation time of PVD's:

$$t = \frac{D^2}{8C_h}\left[\ln\frac{D}{d} - 0.75 + 0.64\pi l^2 \frac{k_c}{q_w}\right] * \ln\frac{1}{1-U_{avg}} \quad (2)$$

Using this formula the following consolidation time can be calculated:

$$t = 3.50 * 10^8 s = \pm 135 \, months$$

This calculated time is significantly bigger than the time needed when using stone columns as a ground improvement.

17. Economical comparison with the proposed solution

To assess the two techniques economically, they will be compared in cost for execution and needed preload embankment for the same consolidation time of 8 months. For this the needed spacing between the PVD's is calculated via the previous formula were the value for L is varied until a consolidation time of 8 months is reached. The calculated spacing is the following: $L = 0.85\ m$. The amount of drains and preload embankment needed is estimated to give a general idea of the cost. The removal of the preload embankment is also taken into account.

Table 13: Comparison in cost

Type	Stone columns	PVD
Total price	€ 7 089 049,60	€ 3 988 621,33
Total price per m²	€ 96,63	€ 54,37

In conclusion, it can be said that the stone columns excel in technical qualities while being the most expensive of the two solutions. Since the stone columns have the extra advantage of being able to carry loads, they are the preferred option in this case. They can both carry the loads of the access ways and outdoor pavements and make sure the consolidation of the soil happens quickly.

18. General conclusions

Firstly, the solution of the main buildings of the project proved to be an interesting mix of pile foundations and embankments to combat settlements of soft soil layers.

Secondly, the solution of the outdoor areas was equally interesting in its combination of ground improvement through vibro compacted stone columns and a preload embankment to neutralize future secondary settlements.

Thirdly, it was found that there are several possible alternatives to the current solution of the main buildings like driven cast in place piles, Atlas screw piles, Omega screw piles and even Franki piles. Their true viability can only be assessed when calculated in the situational parameters of the entire project.

Lastly, prefabricated vertical drains were put against the current solution of vibro compacted stone columns. The stone columns were found to excel in technical qualities while being the most expensive of the two solutions. Since the stone columns have the extra advantage of being able to carry loads, they are the preferred option in this case. The drains were compared based on estimation so further research with all the parameters of the project is desired to make a calculated decision.

19. Future developments

A thorough follow-up of the construction site combined with an analysis of the results of tests during construction will give a more in depth look on how the proposed solution fares. This way the solution can be tested in the field to see if alternatives are needed or not. This field data will make comparing different solutions easier and lead to more efficient designs down the line.

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