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Ground improvement and special foundations at North Lisbon Logistic Platform, plot 1, Portugal

Solutions d'amélioration du sol et fondations spéciales sur la Plateforme Logistique au Nord de Lisbonne, parcelle 1, Portugal

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ABSTRACT: The North Lisbon Logistic Platform is located over soft soils at Tagus river right bank. At the Plot 1 an industrial warehouse with about 100.000 m^2 was built. For the warehouse foundations the following solutions were adopted: i) structural elements: reinforced concrete driven piles; ii) indoor pavements: load transfer platform, granular fill reinforced with geosynthetics, over rigid inclusions, geoconcrete columns (GCC) with under reamed base and capped by stone columns; iii) outdoor pavements: load transfer platform, granular fill reinforced with geosynthetics, over stone columns. The main design and execution criteria are presented, as well as the main results of both site monitoring and full-scale load tests.

RÉSUMÉ: La plateforme logistique du nord de Lisbonne est située sur des sols meubles sur la rive droite du Tage. Sur la parcelle 1, un entrepôt industriel d'environ 100.000 m^2 a été construit. Pour les fondations de l'entrepôt, les solutions suivantes ont été adoptées: i) éléments structurels: pieux battus en béton préfabriqué; ii) revêtements intérieurs: plateforme de transfert de charge, remblai granulaire renforcé de géosynthétiques, sur inclusions rigides, colonnes en géobéton (GCC) avec base sous alésage et coiffées par des colonnes ballastées; iii) revêtements extérieurs: plateforme de transfert de charge, remblai granulaire renforcé de géosynthétiques, sur colonnes ballastées. Les principaux critères de conception et d'exécution sont présentés, ainsi que les principaux résultats du suivi du chantier et des essais de charge en vraie grandeur.

Keywords: Driven piles, rigid inclusions, stone columns; load transfer platform; soft soils

1 INTRODUCTION

The North Lisbon Logistic Platform (NLLP) is located in Castanheira do Ribatejo, Portugal. This platform was built with the intend of creating an interconnection point for international, national and regional logistical flows within the Lisbon and Tagus Valley region. An example of recent construction in NLLP is presented in Lopes et al (2023) .

On plot 1 of the NLLP a new industrial building with an area of approximately 100.000 m^2 was built. In the aerial view in Figure 1, it is possible to identify its location.

The target area of intervention is located on the right bank of the Tagus River, that, from a geological-geotechnical point of view, is dominated by the alluvial terrain of the lower Tagus, characterized by the presence of soft soils with reduced bearing capacity. In the particular area where the new structure is located, the alluvium reaches considerable depths, of the order of 12.0 to 18.0 m, posing serious challenges to the construction of any structure in that location.

Figure 1. Aerial view of the construction site (image taken from Google Earth).

2 GEOLOGICAL AND GEOTECHNICAL CONDITIONS

The site under study fits, from a geomorphological point of view, in the middle of the alluvial plain of the Tagus river, close to the right bank of this main watercourse.

Local geological conditions therefore indicate alluvial formations, of Holocene age, deposited over a sedimentary substrate, called terrace deposits, attributed to the Plio-Pleistocene.

According to the information obtained during the geotechnical investigations, it appears that the local geological-geotechnical scenario is characterized by a layer of surface deposits, developing to a depth variable between 2.0 m and 3.0 m. According to the available sampling, it is a heterogeneous layer made up of a mixture of very soft to medium consistency clays, silts and sands ($0<N_{SPT}<8$). It is considered likely that these materials present an overconsolidated state, as a result of fluctuations in the water table.

Immediately below the layer of surface deposits, to a maximum depth of 12.0 to 18.0 m, there are alluvial soils, essentially made up of (i) very loose to loose sandy-silty horizons detected with thicknesses varying between 1.5 and 6.0 m ($0<N_{SPT}<8$); and (ii) very soft to soft silty clays with thicknesses varying between 6,0 and 11.0 m ($0<N_{SPT}<4$).

Underlying the alluvial layer, there are deposits of Plio-Pleistocene terraces, characterized by the interspersed occurrence of clay, sand and of gravel horizons, all with significant lateral continuity.

As depth advances, an increase in the resistant behaviour exhibited by this formation is observed, as shown by the generally increase of N_{SPT} values in depth, with the lowest values, generally varying between 14 and 30 blows, coming from the top of the formation, showing the occurrence of a more weathered surface zone, with behaviour of moderately dense to dense materials and generally hard to very hard consistency. An exception is made for some specific levels where the SPT tests indicate soft to medium consistency soils among the most compact materials.

The position of the water table is dependent on the water level in the Tagus river, being influenced not only by seasonal variations, but also by the daily tidal cycles felt in the estuary. During the prospecting geotechnical works, the presence of the water table was detected at a depth varying between 1.68 m and 2.12 m.

3 SOLUTIONS

Given the existence of highly compressible cohesive soils, the presence of geological and geotechnical conditions that are globally unfavourable to the accommodation of high and/or persistent loads is evident, with the risk of accentuated and evolving deformable behaviour over time. Consequently, there is a concern about mitigating immediate and deferred deformations, in accordance with the structure serviceability requirements. In this context, the following solutions were adopted:

a) Pile foundations for the warehouse resistant structure;
b) Ground improvement solutions of the foundation soil of interior and exterior pavements using (i) rigid inclusions, using the GEOPIER® GCC system, with a bi-module gravel and concrete cap and (ii) stone columns, using the GRAVA IMPACT® system.

3.1 Pile foundations

The proposed deep foundation solution consists of prefabricated reinforced concrete driven piles, of the TERRA® type, capable of accommodating compression, tension, flexural-compression, flexural-tension and shear loads.

T-350 piles (350x350mm) with a minimum length of 25.0 m were considered, with a seismically reinforced section in the first 12.0 m to be considered from the base of the pile cap. In Figure 2 a photograph of the prefabricated reinforced concrete driven piles on the construction site is presented.

Figure 2. Driven piles.

The stated piles are capped by reinforced concrete pile caps of 1, 2, 3, 4, 5, 6 and 7 piles that, whenever submitted to bending moments that are not possible to accommodate by the binary of forces achieved by axial stresses developed on the vertical piles, are interconnected by a grid of foundation beams, also in reinforced concrete.

Along the peripheral alignment, a solution using sub-verticals piles (10º from the vertical) was also defined. These will have the function of accommodating the vertical and horizontal forces coming from the earth retaining walls on the periphery of the building.

In addition to what was mentioned above, the piles must also be responsible for dissipating the shear coming from the pillars and walls, as well as ensuring the accommodation of the bending stresses developed in depth due to the action of the shear forces.

In Figure 3 a view of the 3D geometric model of the structure's foundation solution is presented.

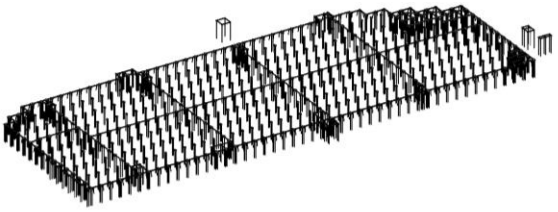


Figure 3. 3D geometric model of the structure's foundation solution (not to scale).

3.2 Ground improvement

Considering the geotechnical conditions described, aiming to reduce total and differential settlements, it was decided to implement, for the indoor pavement as well as the exterior loading/unloading docks pavement area where heavy vehicles will be parked, a ground improvement solution comprising the execution of rigid inclusions, using the Geo-Concrete Columns (GCC®) of the GEOPIER system, with under reamed base, under a load transfer platform, consisting of layers of granular fill reinforced with geosynthetics

The aforementioned rigid inclusions are arranged in different square arrays depending on the magnitude of the expected service live load. In Figure 4 and Table 1, a schematic plan is presented, with the location, spacing and magnitude of the different service live loads considered.

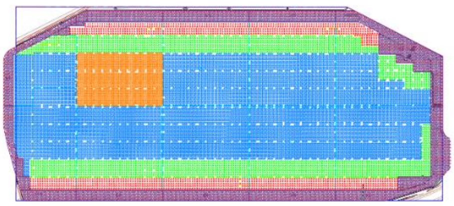


Figure 4. Schematic plan with the ground improvement solutions (not to scale).

Table 1. Live loads and ground improvement techniques considered for the pavement's foundation soil.

Zoning	Live load	System	Spacing
1	75 kN/m^2	GCC Rigid inclusions	2,30 m
2	50 kN/m^2		2,60 m
3	32 kN/m^2		3,10 m
4	20 kN/m^2		3,25 m
5	20 kN/m^2	IMPACT Stone columns	2,50 m

Prior to the installation of the rigid inclusions, in order to reach the levels foreseen for the pavements, an embankment with an average thickness of approximately 2.0 m was built. In this context, to minimize the excavation works, it was decided to execute pre-drilling works and install a stone column cap on top of the concrete columns.

For the exterior pavements, in the area intended for car traffic, likewise aiming to minimize total and differential settlements, a ground improvement solution using stone columns, using the GRAVA IMPACT® system was adopted. The stone columns are arranged in a triangular mesh spaced 1.2 m, under a load transfer platform, consisting of layers of granular fill reinforced with geosynthetics.

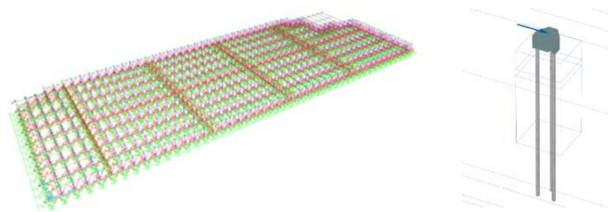
In Figure 5 a photograph of the load transfer platform is presented.

Figure 5. Load transfer platform.

4 DESIGN

4.1 Pile foundations

The foundations as well as the building's structure were modelled using the SAP2000 finite element software, in which the various structural elements were represented with their true dimensions and stiffness. In Figure 6 the 3D foundation model is presented.



a) *b)*

Figure 6. a) Foundation's structure 3D SAP2000 finite element model. b) Pile Plaxis 3D finite element model.

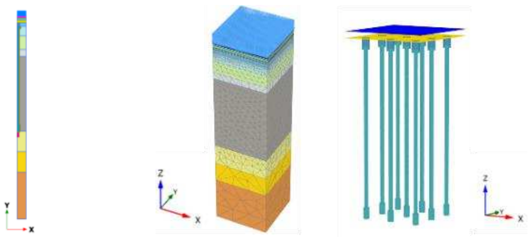
For a more realistic analysis of the forces and displacements to which the structure and its foundations will be subjected, spring elements with vertical, horizontal and flexural stiffness of the various types of pile cap and prefabricated piles in each vertical structural element (columns and façades) were considered. The vertical and flexural spring stiffness were estimated based on the vertical static load tests carried out. The Plaxis 3D finite element software was used to determine the horizontal stiffness of the piles, as well as to quantify the axial stresses due to the effect of negative skin friction and bending moment distribution along the piles.

4.2 Ground improvement

The study of the ground improvement solutions was based on an initial calibration phase through stress-strain analyses, namely, two-dimensional finite element analysis, in axisymmetry condition, using the Plaxis 2D software, simulating two of the static vertical load tests carried out on site.

In a second phase, the project ground improvement solutions were modelled, also through two- and three-dimensional finite element analysis using the Plaxis 2D and Plaxis 3D software respectively.

With this analysis the stresses, strains and displacements in the rigid inclusions, stone columns and geosynthetics were estimated. The settlements on the pavements were also calculated and compared with the floor's serviceability requirements. In Figure 7 some of the 2D and 3D calculation models are presented.



a) *b)*

Figure 7. Ground improvement finite element calculation models a) Plaxis 2D, axisymmetry conditions. b) Plaxis 3D.

5 MONITORING AND FULL-SCALE LOAD TESTS

Prior to the execution of the work, a set of static and dynamic load tests on vertical prefabricated driven piles were carried out. The aforementioned tests allowed the analysis of the behaviour of the piles with regard to force-settlement curves, being therefore fundamental elements in the design stage.

As part of the quality and execution control of the stone columns, as well as the GCC rigid inclusions, a set of static vertical load tests were also carried out, considering loads higher than the expected service load.

Additionally, in order to evaluate the performance of the ground improvement solution in the medium and long term, a full-scale test was carried out, through the construction of an experimental landfill over four GCC rigid inclusions lasting approximately 5 months, up to 200% of the service load. The results, presented in Figure 8, confirmed that the expected settlement was inferior to the considered admissible value. In Figure 9, it is possible to view the full scale and static vertical load tests.

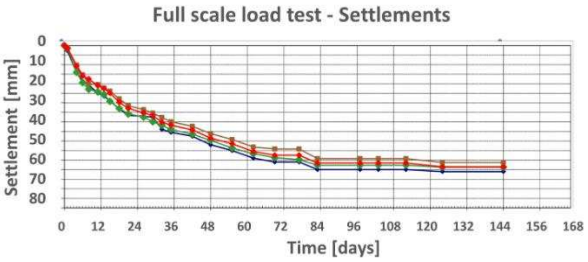


Figure 8. Full scale load test – Settlement evolution over time.

a) *b)*

Figure 9. a) Full scale load test. b) Static vertical load test.

6 FINAL REMARKS

The framework of the work described determined the need to develop economic foundation solutions compatible with the structure serviceability.

In this context, it should be noted that the adopted ground improvement solutions allow for the reduction, in the foundation structural elements, of the design seismic horizontal forces originating from the expected high magnitude pavements live loads.

It also made it possible to reduce shear stresses and bending moments at the floor slab, thus allowing for considerable savings in the reinforced concrete pavement structure.

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