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FOUNDATION DESIGN AND STRUCTURAL INTEGRATION FOR A NEW HOSPITAL IN FARO, PORTUGAL

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ABSTRACT

This paper outlines the foundation design for the Lusíadas Private Hospital in Faro, developed through a collaborative effort involving structural, architectural, and geotechnical teams. Tailored to address the site's complex geological and geotechnical conditions, the solution integrates finite element modelling and empirical analysis.

Finite element analysis tools, namely PLAXIS 2D and 3D, were utilized to simulate stresses, deformations, and stability under various load scenarios. These models verified the interaction between soil and structural elements, assessing ultimate and service limit states in compliance with the Eurocodes.

The design process involved close coordination with the building design to align foundation solutions with stability and architectural requirements. The foundation system features cast-in-place and driven piles, optimized for axial compression and flexure. Load distribution from the superstructure and installations was carefully analyzed to ensure safety and efficiency, using methods like the Bustamante and Gianeselli approach.

During construction, the design was continuously validated and adjusted as needed based on real-time assessments of geological and hydrogeological conditions. The integration of empirical data and advanced simulation ensured a robust design adaptable to unforeseen site conditions.

Keywords: foundation design, soil-structure interaction, geotechnical analysis, geotechnical modelling.

INTRODUCTION

The southern region of Portugal, near the Atlantic Ocean shoreline, has seen a population increase in recent years. To meet the growing demand, a hospital from the private health group "Lusíadas" was designed to address this specific need.

Due to economical and logistics reasons, a precast concrete solution was developed in two phases:

1. Execution of the foundations and infrastructure in situ;
2. Installation of the precast concrete structure.

SITE SEISMIC CHARACTERIZATION

The project is located in a seismic active region, and its design was guided by the parameters defined in the NP EN 1998-1:2010 standard. According to this regulation, the site falls within Seismic Zone 2.3 for Type 2 seismic action, with a reference peak ground acceleration of 1.7 m/s².

These values were taken into account in the geotechnical and structural analysis to ensure appropriate seismic performance of the foundation system.

GEOLOGICAL AND GEOTECHNICAL CONDITIONS

A site investigation comprised of 6 boreholes was conducted. From those boreholes, samples were extracted to access the geotechnical properties of the intercepted strata.

Based on the retrieved information, 11 geological and geotechnical profiles were defined:

Table 1 Geological and Geotechnical Profiles

Soil Unit	Description	N _{SPT}
11	Heterogeneous fill of non-selective origin	-
10	Clayey-silty sand to clayey sand, sometimes with gravel	5-10
9	Lean clay with sand to sandy lean clay	9-15
8	Sand, sometimes with silt and gravel	11-30
7	Clayey-silty sand to clayey sand, sometimes with gravel	11-30
6	Lean clay with sand to sandy lean clay	16-30

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Soil Unit	Description	N _{SPT}
5	Sand, sometimes with silt and gravel	31-60
4	Clayey-silty sand to clayey sand, sometimes with gravel	31-59
3	Lean clay with sand to sandy lean clay	31-59
2	Clayey-silty sand to clayey sand, sometimes with gravel	>60
1	Irregularly consolidated biocalcarene	>60

Groundwater conditions were assessed through piezometric measurements carried out at the time of the project. The water table was detected at a depth of approximately 17 meters, indicating that, under static conditions, groundwater effects on the foundation elements would be minimal in the upper soil strata.

FOUNDATION SOLUTION

The site investigation assessment revealed that the superficial soil layers were not suitable for a shallow foundation, considering the type of structure and the area's intense seismic activity.

There are empirical guidelines from Fellenius (2015), that define the design process for deep foundations. The loads are resisted by lateral friction and end bearing capacity of the piles. The design method should comprise of 4 phases:

- Preliminary study where the viability of the solution is analysed;
- Mapping of the piles and definition of their general characteristics;
- Detailed study of the optimal number of piles;
- Estimation of settlements, axial loads, shear and bending moments at the piles.

The final design of the foundation elements assesses the following:

- Ultimate bearing capacity for axial, shear stresses, and bending moments of the piles;
- Maximum total settlement, at any point of the foundation;
- Differential settlements, experienced between two points.

Early in the study, two types of solutions were studied to optimize construction costs, execution processes and structure/geotechnical performance: precast driven piles vs bored piles.

NUMERICAL MODELS

This foundation design required the integration of several numerical models for different types of analysis:

- To study the building structural behavior, both for serviceability and ultimate limit states, SAP2000 finite element models (FEM) were assembled with linear springs derived from the settlements obtained in the PLAXIS models. This process was iterated several times before reaching convergence (between load distribution within the structure, and the springs at the base of the model).
- PLAXIS 2D axisymmetric FEM analysis was conducted to study the behavior of the piles in the ground.
- For the foundation design and settlement assessment, PLAXIS 3D models were used to carry out FEM analysis, calibrated from the PLAXIS 2D models, and interactively updated from the structural models mentioned above.

Characteristic drained soil parameters were derived from site investigations and historical data. The Hardening Soil Model was used in the FEM Plaxis 2D analysis (Table 2).

Table 2 Hardening Soil Parameters

Soil Unit	γ [kN/m ³]	E_{so}^{ref} [Mpa]	c' [kPa]	Φ' [°]
11	18	5	7	26
10	19	8	5	28
9	20	15	15	27
8	20	25	0	34
7	20	20	10	30
6	21	30	25	29
5	21	40	0	36
4	21	30	15	31
3	22	60	45	30
2	22	70	30	34
1	This unit (rock) was found at a depth of 40+ meters. Due to its depth, it was not considered in the models.			

PRECAST DRIVEN PILES VS BORED PILES

To compare the performance of precast driven piles (350x350mm and 400x400mm) vs bored piles (Ø800mm and Ø1000mm), 2D axisymmetric models, using PLAXIS 2D, were constructed.

The analysis mainly focused on understanding the behaviour of the piles when subject to axial load. Piles were loaded at 8MPa on their heads, and Driven Piles (D.P.) were simulated with 3 different lengths: 10m, 15m and 20m. The load-settlement results are shown in Figure 1 below.

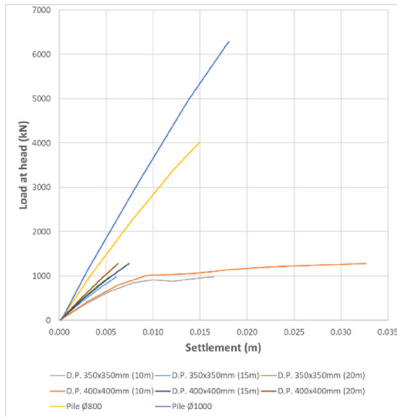


Figure 1 Pile axial load tests - PLAXIS 2D

From these results it was possible to make an estimation of the correspondence between the number of driven piles vs bored piles to then come to conclusions about the effectiveness adopting one or the other in terms of settlement control and economy.

FOUNDATION DESIGN

To implement and study the foundation solution for the hospital building, a 3D FEM analysis was carried out using PLAXIS 3D.

This analysis had three main goals:

1. Reach convergence between the calculated settlements (output) and loads from the structural models (input);
2. Study global and differential settlements (according to Eurocodes 2 and 7) once convergence has been reached, and iterate again if needed;
3. Evaluate structural capacity of the piles.

To reach convergence between the geotechnical and building structural models, the iterative process comprised the following stages:

1. Estimation of linear springs from 2D axisymmetric axial testing, where rotations at the base of the columns was calculated from binary forces between piles;
2. Input the results of the structural model (with springs at the base of the building columns) to the geotechnical 3D model, at the pile caps;
3. Process the settlements obtained from

the geotechnical model and recalculate springs;

4. Repeat steps 2 and 3 until convergence has been reached (between load distribution within the structure, and the springs at the base of the model).

RESULTS

As previously mentioned, the foundation design is essentially split between two types of safety checks:

- Serviceability Limit States;
- Ultimate Limit States.

The study of the foundation behaviour during service conditions was made in terms of settlements. Figure 2 and Figure 3 show the vertical deformation obtained in the 3D model for the bored piles (1000mm diameter) and the driven piles (35cm and 40cm square sections). These results were calibrated from the 2D axisymmetric load tests.

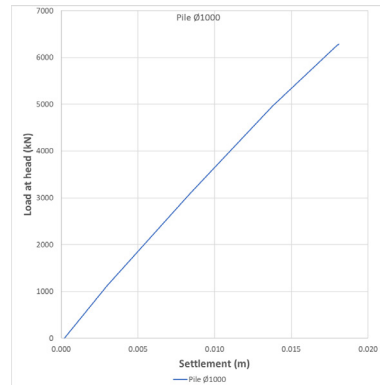


Figure 2 Load-settlement curve for the Ø1000 bored piles

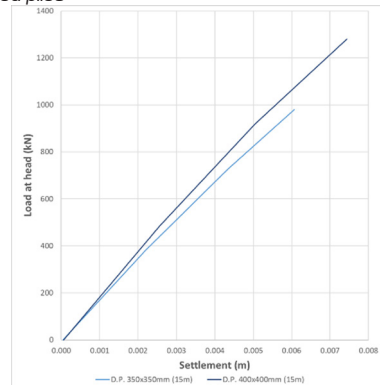


Figure 3 Load-settlement curve for the driven piles (35 and 40cm square sections)

To check the differential settlements, the maximum rotations over two points in the foundation system were estimated.

Equation (1) shows the formula used to check the rotations:

$$\tan(\theta_{\text{rel,max}}) = \tan\left(\frac{(\delta_{\text{max}} - \delta_{\text{min}}) \times 10^{-3}}{\text{distance}}\right) \quad (1)$$

where $\theta_{\text{rel,max}}$ is the rotation (angle) between two points with the settlements δ_{max} and δ_{min} .

To ensure the structural integrity and safety of the foundation, the following critical checks were conducted:

- **Bearing Capacity:** to ensure the pile can support the applied loads without reaching failure. Assess the interaction between the pile and surrounding soil to prevent excessive settlement or failure.
- **Structural Resistance:** Verify the pile's structural integrity under maximum loads.

The bearing capacity was calibrated in the 3D models according to empirical methods proposed by Bustamante, M. and Gianeselli, L. (1993 and 1998). The embedded beam elements used to simulate the interaction between the pile and the surrounding soil, ensuring realistic modelling of both axial and lateral load responses.

Regarding the structural capacity, the piles were designed to withstand seismic loading, by balancing the basal forces across the foundation caps. The following figures show the structural design of the piles, with maximum bending moments of 1543kNm and maximum shear of 867kN (Figure 4 and Figure 5).

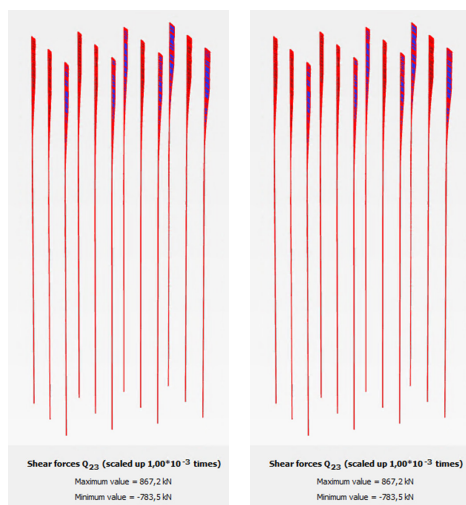


Figure 4 Shear forces and moments in the piles retrieved from the 3D Model

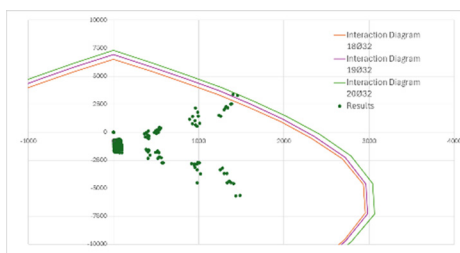


Figure 5 N-M3 Interaction diagrams for the structural capacity of the piles

FINAL REMARKS

This study concluded that the combination of driven piles and bored piles offers significant advantages in the following areas:

- **Economy:** the hybrid foundation system allowed for optimized material usage by leveraging the cost-effectiveness of each pile type.
- **Execution Time:** by strategically combining driven and bored piles, construction phases were streamlined, resulting in shorter execution times and improved project scheduling.
- **Efficiency:** the combined system provided enhanced load distribution and better adaptability to varying soil conditions, increasing overall structural performance and foundation reliability.

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