Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-514

Excavation, earth retaining solutions and facades underpinning of a historic building in Estoril, Portugal

Excavation, solutions de soutènement des terres et reprise en sous-œuvre des façades d´un bâtiment historique à Estoril, Portugal

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ABSTRACT: This paper aims to present the solutions for excavation, peripheral earth retaining walls and centenary facades underpinning of a future residential building, located in Estoril, Cascais, Portugal. Firstly, to preserve the building´s facades, a temporary structural system was installed, allowing the facades bracing, ensured by the execution of horizontal steel distribution beams and vertical steel frames, founded on vertical micropiles. Secondly, the facades were underpinned through the execution of two twin underpinning beams, connected by pre-stressed bars, founded also on vertical micropiles. For the execution of the underground floors, it was necessary to excavate a maximum of 9 m under the original building´s foundations, using the king post walls earth retaining technique braced horizontally by steel props, ensuring the compatibility of the underpinning and the retaining facades solutions. Lastly, the monitoring and observation of the peripheral retaining structure and facades is also pointed out, encompassing detailed analyses and comparisons with the initially estimated values from the design phase.

RÉSUMÉ: Cet article vise à présenter les solutions pour l'excavation, les murs de soutènement périphériques et la reprise en sous-œuvre des façades centenaires d'un futur immeuble résidentiel situé à Estoril, Cascais, Portugal. Tout d'abord, pour préserver les façades du bâtiment, un système structurel temporaire a été installé, permettant le contreventement des façades assuré par la réalisation de poutres de distribution horizontales en acier et de cadres verticaux en acier, fondés sur des micropieux verticaux. Deuxièmement, les façades ont été soutenues par l'exécution de deux poutres de soutènement jumelles, reliées par des barres précontraintes, également fondées sur des micropieux verticaux. Pour l'exécution des étages souterrains, il a été nécessaire d'excaver jusqu'à une profondeur maximale de 9 m sous les fondations originales du bâtiment, en utilisant la technique de soutènement des murs à paroi berlinoise, contreventée horizontalement par des étais en acier, assurant la compatibilité entre le soutènement et les solutions de soutènement des façades. Enfin, la surveillance et l'observation de la structure de soutènement périphérique et des façades sont également soulignées, englobant des analyses détaillées et des comparaisons avec les valeurs initialement estimées lors de la phase de conception.

Keywords: Earth retaining structures; king post walls; underpinning; facades; micropiles.

1 INTRODUCTION

The present article outlines the solutions adopted for the retention and underpinning of an existing old facade, as well as for the excavation and peripheral earth retaining structure, enabling the construction of an underground parking lot for a future residential building.

Within the intervened plot, there was a vacant building whose main facades were, for the most part, preserved. The exterior walls were composed by ordinary stone masonry, with a thickness of 0.80 m, decreasing in height. Generally, the facades exhibited a considerable state of degradation, particularly on the southern facade, with the possible risk of partially collapsing. Figure 1 presents an aerial perspective of the intervention site before the construction work´s.

Figure 1. Aerial view of the intervention site, in its current state.

The new building will be situated on Avenue Senhora Monte da Saúde, covering an approximate ground area of 670 m^2. It will comprise a parking lot, a ground floor, three elevated floors and a slopping roof. The intervention area, within which the building is situated, encompasses around 1446 m^2. Figure 2 depicts a virtual view of the future residential building.

Figure 2. Virtual view of the future residential building.

2 MAIN CONSTRAINTS

2.1 Geological and geotechnical conditions

To characterize the geotechnical behaviour, associated with the soils present at the site, a prospecting campaign was conducted involving the execution of two mechanical boreholes accompanied by Standard Penetration Tests (SPT) and the collection of samples for macroscopic classification. Additionally, one hydraulic piezometer was installed in one of the boreholes.

According to the results obtained, the geological structure of the site is characterized, superficially, by the presence of Landfill Deposits (At) mainly composed of rocky blocks and clayey sands with an average thickness of 1.0 m. Notably, no standard penetration test was conducted on these modern anthropogenic materials. Subsequently, underlying these fill deposits, Cretaceous formations (C^1_{Ba} e C^1_A) are manifested at this location by three geotechnical horizons. The conducted borehole surveys unveiled the presence of clays and sandy clays (ZG_{2A} - C^1_{Ba}), with variable thickness ranging between 7,50 m and 10,50 m and N_{SPT} values ranging from 15 to 41 blows. Addtionally, fine clayey sands to sandy clays (ZG_{2B} - C^1_{Ba}) were encountered at depths varying from 7,5 m and 12,0 m, with N_{SPT} values spanning from 23 to 46 blows. Lastly, a lower stratum was characterized by moderately to highly altered and fractured limestones (ZG_{2C}-C^1_A), interspersed with fine-grained sandstones, in which Rock Quality Designation (RQD) values ranged from 32% to 49%. This unit was identified at the dephs of 10.0 m and 11.8 m.

In terms of hydrogeology, there is no water level at the excavation site according to the conducted survey, which should not interfere with the local hydrogeological regime.

2.2 Neighbourhood conditions

The excavation site is situated in an urbanized area, bounded by Avenue Senhora Monte da Saúde to the West, and several other neighbouring constructions. To the North, the plot is bordered by two residential buildings with two and three elevated floors, respectively, and both without underground basements. To the South, it is delineated by the backyard and annex of a neighbouring plot. To the East, it is surrounded by a one-story church, also without underground basements.

Additionally, it is worth noting the presence of party walls along the lot boundaries and the proximity of an existing wall, located inside the lot, to the proposed king post wall solution at the rear of the façade to be preserved. In Figure 3 it is possible to observe the main boundaries of the excavation site.

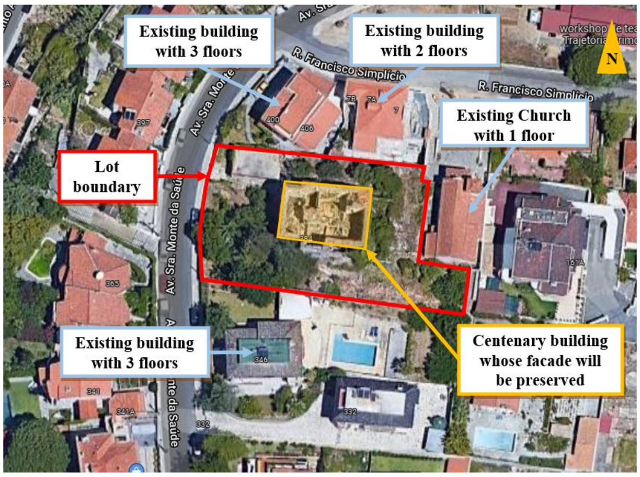

Figure 3. Main boundaries of the excavation site.

3 ADOPTED SOLUTIONS

3.1 Facades retention and underpinning

Given the facades high deterioration level, particularly on the southern side, and the need to demolish/dismantle a portion of it, it was decided that, prior to the facades retention work, an extensive treatment to the existing cracks should be undertaken through the injection of grouts based on hydraulic lime. Subsequently, steel angle profiles were installed at the corners of the facades to be preserved, and three levels of tensioned 26 mm galvanized tie rods were installed to ensure the maximization of safety during the facades retention works (Figure 4).

Figure 4. Prior facade retention works, involving the installation of steel angles and steel tie rods per floor.

The facade retention structure was composed by steel distribution beams, which had the primary objective of equalizing horizontal loads on the wall and directing it towards 8 bracing frames, particularly loads induced by wind action. These distribution beams were constituted by HEB 180 and UPN 260 steel profiles, while the bracing frames were constructed using steel trusses comprised by HEB 240 vertical columns, HEB 200 horizontal beams and LNP 150x150x10 diagonal steel angles.

In order to provide an appropriate foundation with adequate stiffness and strength for the bracing frames of the retention structure, considering tensile and shear forces to which the structure might be subjected, reinforced concrete massif´s were executed, indirectly founded on micropiles. The micropiles were executed using N80 Ø139.7x10mm profiles with external connections between sections and sealed through the Repeated and Selective Injection system (IRS), in competent and geologically stable ground, with N_{SPT} > 60 blows.

To underpin the facades, a system composed by two rows of micropiles was designed, connected by two underpinning beams (one on the exterior and another on the interior of the existing walls), joined by prestressed Gewi type bars. In Figure 5 , the defined facades retention and underpinning solution can be observed.

Figure 5. Facades retention and underpinning solution.

Additionally, given the high deterioration level of the facades, there was the need to reinforce the stone masonry walls by executing a reinforcement wall with a thickness of 8 cm. This wall consisted of a reinforcement mesh and shotcrete, executed from the interior and securely anchored to the existing facades (Figure 6). Upon completion of the facades retention and underpinning works, excavation and peripheral containment activities were initiated.

Figure 6. Strengthening of stone masonry walls with a reinforced concrete layer.

3.2 Excavation and peripheral earth retaining structures

The excavation and peripheral earth retaining structures were executed following the King Post Wall technology, with careful consideration given to compatibility with the facades retention and underpinning works. This solution involved a phased construction, from top to bottom, of reinforced concrete panels. The process commenced with the execution of the primary panels, followed by the secondary, and ultimately, the tertiary panels.

The panels were horizontally braced by provisional elements such as steel props, tie rods and temporary pre-stressed ground anchors, and vertically supported by micropiles. The bracing elements were composed by HEB 180 and HEB 220 steel profiles, braced by HEB 120 profiles with S275 JR steel grade. In convex corners, resistance to impulses was ensured by pre-stressed Gewi tie rods.

The executed ground anchors comprised 4 strands, each with a diameter of 1.5 cm, and with a tensile load of 450 kN. The bonded lengths were accomplished using the IRS system, incorporating double obturators and non-return valves, with a minimum hole diameter of 200 mm and minimum length of 4.0 m. To prevent potential intersections with existing infrastructures and structures, as well as to allow proper sealing in competent and geologically stable soil, these anchors were inclined at 30.0º and 35.0º horizontally.

Vertical micropiles were designed to support the vertical loads imposed on the peripheral earth retaining structure, particularly by the self-weight and by the vertical component of the ground anchors. These elements were executed using N80 Ø139.7x10.0 mm tubular profiles with external joints, made of high-strength steel ($f_{syd} > 560$MPa), placed inside a 200 mm hole diameter and bonded for a length of 6.0 m, using the IRS system. The micropiles were connected at the top by capping beams and were generally embedded in the king post walls, which had a thickness of 0.30 m.

In Figure 7, the excavation and peripheral earth retaining solution are depicted.

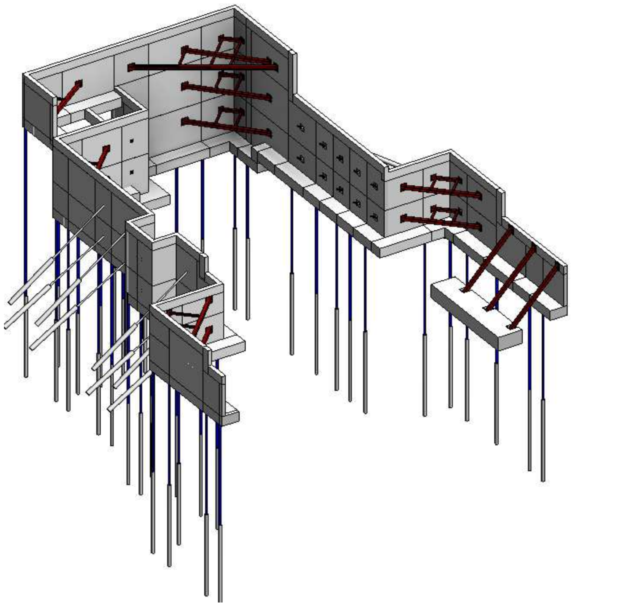

Figure 7. Excavation and peripheral earth retaining solution (BIM model in software Revit).

4 GEOTECHNICAL AND STRUCTURAL DESIGN

4.1 Facades retention and underpinning

The behaviour of the facades retention structure was analysed in terms of forces, reactions and deformations using finite element models created in the Autodesk Robot Structural Analysis Professional 2022 software (Figure 8). This allowed the simulation of the wind effects, the most critical factor to this case. The facades bracing system was modelled in the program using "steel members" type elements with their respective mechanical properties. The micropiles were depicted as fixed supports.

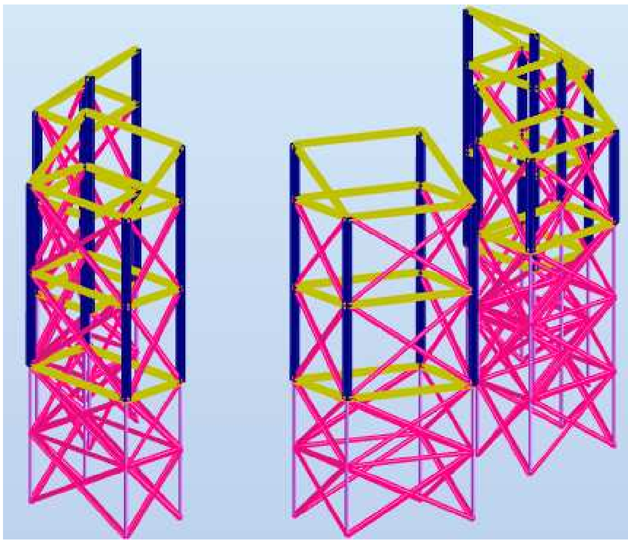

Figure 8. Facades retention structural model, developed in Robot software.

4.2 Excavation and peripheral earth retaining structures

The assessment of the presented peripheral earth retaining solution in terms of forces and deformations was conducted for all major construction phases using a finite element program, PLAXIS 2D. A constitutive model was developed to simulate the soil behaviour characteristics of a "Hardening Soil", considering a nonlinear constitutive relationship and variations in the soil's stiffness under applied stress states. In the context of soil geomechanical parameterization, the reference values obtained from the geological-geotechnical study were incorporated in PLAXIS software, to simulate the soils behaviour, as detailed in Table 1.

Table 1. Geotechnical soil parameters.

Soil Type	ZG_1	ZG_{2A}	ZG_{2B}	ZG_{2C}
N_{SPT}	-	15-41	23-46	> 60
Υ [kN/m^3]	19	20	20	21
Φ [º]	25	-	35	35
c_u/c´ [KPa]	-	90	1	5
$E_{50}{}^{ref}$ [MPa]	7,5	30	50	180
$E_{ur}{}^{ref}$ [MPa]	22,5	90	150	540
m [-]	0,5	0,7	0,9	1

Soil Type: ZG_1 – *Loosely compact sandy-clay fill*; ZG_{2A} – *clay and sandy clay soil;* ZG_{2B} – *fine clayey sand to sandy clay soil;* ZG_{2C} – *fractured limestones interspersed with fine-grained sandstones.*

Soil Parameters: *Υ – Volumetric weight; Φ' – effective friction angle; $E_{50}{}^{ref}$ – elastic modulus corresponding to 50% of the ultimate tensile stress defined for a reference pressure (p_{ref} = 100kPa); $E_{ur}{}^{ref}$ - elastic modulus for unloading/reloading at a stress level equal to the reference pressure (p_{ref} = 100kPa); m – power that controls the stress dependency of the elastic modulus.*

In the developed models, the king post walls and micropiles were modelled using "plate" elements with elastic behaviour. However, the zones corresponding to the free length and the bond lengths of the micropiles were modelled using "embedded beam row" elements. The temporary ground anchors were modelled using "node-to-node anchor" elements and their respective bond lengths were modelled using "embedded beam row" elements. The steel props were modelled using "anchors", with the equivalent stiffness to the defined bracing system.

The behaviour of the peripheral retainment structure was analysed for the main excavation phases, assessing crucial design parameters such as forces of the containment structures, deformations, stress states and stability of the soils to be contained. The bonded lengths of the micropiles and temporary ground anchors were determined according to the methodology proposed by Bustamante and Doix (1985). Figure 9 and Figure 10 present the deformed mesh of the developed PLAXIS models.

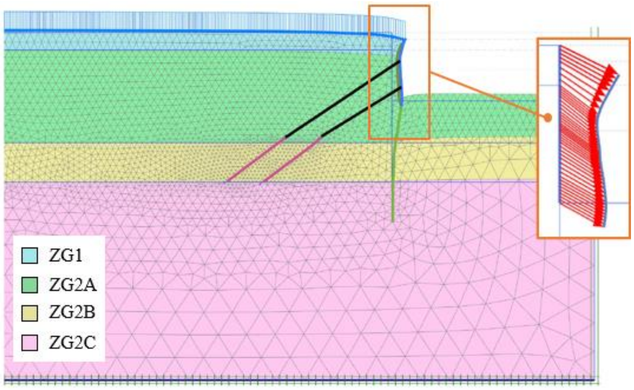

Figure 9. Deformed mesh of the excavation´s base level phase - King post walls braced by pre-stressed ground anchors.

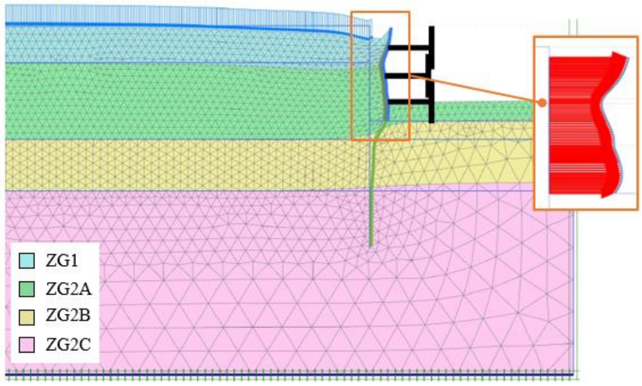

Figure 10. Deformed mesh of the excavation´s base level - King post walls braced by steel props.

The maximum horizontal displacement estimated for the king post wall supported by two levels of pre-stressed ground anchors was 10,90 mm, for a total excavation height of 5,90 m (L/540), meeting the ELS requirements.

For the scenario in which the earth retaining structure is braced by three levels of steel props, for a total excavation height of 8,20 m, the maximum horizontal displacement estimated was 9,40 mm (L/870), meeting the ELS requirements.

5 MONITORING AND SURVEY PLAN

The established Monitoring and Survey Plan (MSP) on site had as its main objective to ensure the safe execution of the demolition, retention and underpinning works of the facades, as well as the peripheral earth retaining structure of the underground floors. Additionally, it aimed to analyse the behavior of neighboring structures and infrastructures during the construction works.

In the initial phase, for the control of displacements, rotations and measurement of masonry wall crack openings during the demolition and reinforcement of existing structures, an automated monitoring system was implemented for a 2-month construction period.

The entire field data reading and acquisition system were fully automated, with readings taken every 1 hour. Sensors were installed for data acquisition and transmission to a wireless web platform. Figure 11 illustrates the application of the web monitoring system for this specific construction project.

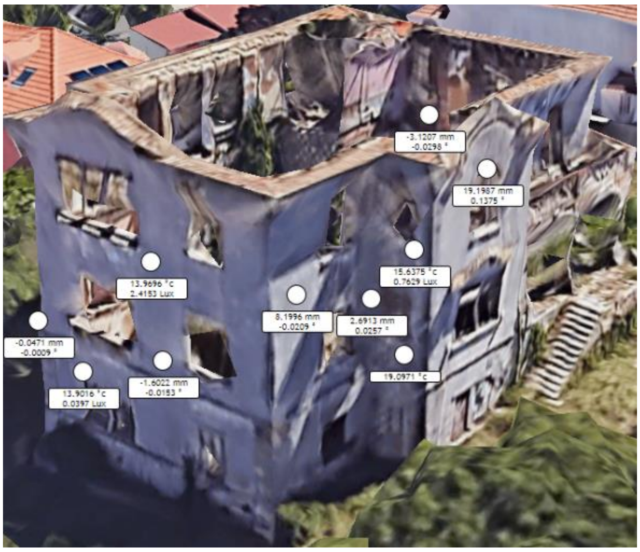

Figure 11. Aerial view of the intervention site (Google Earths image) – Web Monitoring System

The implementation of this automated monitoring system not only enabled a more accurate and systematic control of the behaviour of all critical structures, but also streamlined the adjustment of construction methodologies during the execution of the new structures, potentially resulting in enhanced productivity.

The implemented MSP on the existing facades included the following fully automated sensors/instruments:

- 12 triaxial tiltmeters for measuring rotations and displacements of the preserved facades and neighboring structures and infrastructures;
- 4 vibrating wire crackmeters (strain gauges) for measuring crack openings;
- 40 manually read crackmeters for measuring crack openings;
- 2 Gateways, which correspond to the data collection and network data transmission system via 3G;
- 2 solar panels for energy supply to the Gateway.

In the second phase, for excavation and peripheral earth retaining construction works, the following instruments were installed, for a 6-month construction period:

- 14 triaxial tiltmeters placed on the king post walls, to measure rotations and displacements;
- 4 electric load cells, to measure the pre-stressed loads applied to the temporary ground anchors;
- 1 inclinometer positioned behind the peripheral earth retaining walls, to measure horizontal and vertical displacements of the retaining walls;
- 1 piezometer to measure underground water pressure.

Based on the conducted modelling, alert and alarm criteria was established for all instruments and monitored structures.

6 CONCLUSIONS

In the scope of this article, it is expected to demonstrate the technical efficiency of the facades retention and underpinning solution as well as the king post walls solution, braced by various structural elements, such as struts and temporary ground anchors. Furthermore, it is expected that the peripheral earth retaining solution present´s actual displacements lower than those estimated in design and display a highly stable behaviour during the excavation works currently underway.

ACKNOWLEDGEMENTS

The authors express their gratitude to PRET INVESTIMENTOS, the Project Owner, for granting permission to publish this article. The described works were performed by ENGCON (general contractor) and GEOSOL (geotechnical works contractor).

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