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Extension of the Lisbon subway between Santos station and the Terminal of the Cais do Sodré station - assessment of excavation induced damage in buildings

Extension du métro de Lisbonne entre la Gare Santos et le Terminal de la gare Cais do Sodré – evaluation des dommages causés pour les travaux d'excavation sur les constructions

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ABSTRACT: The expansion of Lisbon's Underground network through the Yellow and Green lines extension project is taking place in a densely urbanized area of Santos and Cais do Sodré. The area, close to the Tagus River, combines challenging ground conditions and a large diversity of vulnerable assets, including heritage listed buildings, residential buildings and major utilities companies' assets. The project comprises the construction of the new Santos station and adjacent tunnels using the Conventional Method. The construction works will employ a sequential excavation method through poor ground conditions and low ground cover, including sections with less than one diameter of ground cover between the tunnels and the surface. In order to reduce the risk of damage to the buildings located in the zone of influence of the excavation works, a comprehensive damage assessment study was carried out in the initial stage of the project to assist the design of the tunnel primary lining and cut & cover retaining walls. This article will present the key challenges faced by the design team and the adopted solutions to reduce the risk of damaging the existing assets.

RÉSUMÉ: L'expansion du Métro de Lisbonne comprend d'extension de la lignes Jaune et Vert se développe dans une zone densément urbanisée de Santos et Cais do Sodré. La zone, proche du Tage, combine des conditions de sol difficiles et une grande diversité d'actifs vulnérables, particulièrement, édifices historiques, des édifices résidentiels et des actifs de services publics. Le projet comprend la construction de la nouvelle gare de Santos et des tunnels adjacents selon le méthode conventionnelle NATM (New Austrian Tunneling Method). Les travaux de construction utiliseront une méthode d'excavation séquentielle dans un massif avec faible résistance, y sections avec moins d'un diamètre de couverture entre les tunnels et la surface. Afin de réduire le risque de dommages aux édifices situés dans la zone d'influence des travaux souterrains, une étude complète d'évaluation des dommages a été réalisée dès la phase initiale du projet pour aider à la conception du tunnel, à la séquence d'excavation et au soutènement primaire. et calcul des structures de soutènement. Cet article présentera les principaux défis rencontrés par l'équipe de projet et les solutions adoptées pour réduire le risque de dommage des édifices.

Keywords: Building damage assessment; ground movements; damage assessment model and mitigation measures.

1 INTRODUCTION

The extension of the Yellow and Green lines is the most significant upgrade to Lisbon's subway network in the last decade. By creating a new connection between two existing lines (Green and Yellow), this project will form a circle line which will enhance the usability of public transportation services in the city centre (Figure 1). Construction works started in 2021 and passenger services are planned to start in 2025.

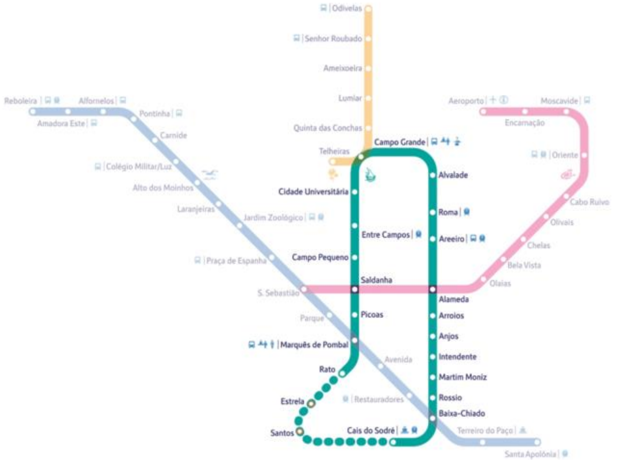

Figure 1. Lisbon's subway network (Metropolitano de Lisboa).

The project comprises a total of 1984 metres of running tunnels, two new underground stations, station upgrades at Rato and Cais do Sodré stations and a new flyover at Campo Grande. Works are divided into four lots, with Lots 1 and 2 splitting the civil works, Lot 3 includes the Campo Grande Flyover and Lot 4 includes all Mechanical, Electrical, Public Health and Architectural works.

This paper provides an overview of the building damage assessment analysis carried-out for Lot 2. This lot comprises 664 metres of new railway tunnels, running from the new underground station at Santos to the existing Cais do Sodré station (Figure 2).

The ground conditions change significantly along the route of the project, with Miocénic and Lisbon's Vulcanic formations at Santos' station, gradually changing to Tagus' River Alluvium Deposits at Cais do Sodré station.

The excavation works comprise deep shaft excavation, NATM/SCL tunnelling for the station platform tunnels, running tunnels and Cut and Cover excavations.

The zone of influence of the excavation works is a medium density urbanised area of Lisbon's downtown area. As part of the damage assessment analysis, 104 assets were analysed, comprising residential buildings, commercial buildings, listed buildings, railway lines and utilities. This paper will only cover the building damage assessments.

Figure 2. Plan view of Lot 2 (Yellow and Green lines extension project).

The damage assessment analysis provided essential information regarding the expected response of structures to ground movements induced by the excavation works. This allowed the design team to effectively adjust the construction methodology and, where required, to design ground movement mitigation measures. The requirement for ground movement mitigation measures to be implemented was identified by the damage assessment analysis. The efficiency of these measures was also confirmed by the damage assessment analysis. The ground movement mitigation measures included modifications to the construction methodology, underpinning of buildings, ground movement reduction barriers and structural bracing of buildings.

In areas where vulnerable buildings were located, the construction methodology for tunnels was adjusted to reduce the ground movements to the required magnitude to avoid damage.

The monitoring plan also was developed considering the output from the damage assessment analysis.

This paper provides an overview of the methodology adopted by the design team to develop the building damage assessment and how its output was used to assist on decisions regarding the construction methodology, the application of ground movement mitigation measures and the monitoring plan. An example of the implementation of this methodology to one of the buildings is presented in this paper.

2 METHODOLOGY

2.1 Building damage assessment model

The damage assessment analysis was part of the detailed design for the civil works. The analysis started with the development of a damage assessment model using specific software (Oasys Xdisp Pro). This software automates building damage assessments based on Burland's (1995) assessment method. The model covered the full length of the project, including all the assets and excavation works (Figure 4).

In parallel, condition surveys were conducted to assess the condition of each building in the zone of influence of the excavation works. The condition surveys provided the design team with valuable information reg to understand the structure type (i.e. concrete framed or masonry), the type of foundation (i.e. shallow or deep foundations) and preexisting damages.

Each asset was defined in the model considering its generic dimensions (layout, foundation level, height, and structure type).

The building damage assessment analysis followed the staged risk assessment approach (Burland, 1995), which includes a preliminary assessment, a second stage assessment and detailed evaluation.

A total of sixty-eight buildings were damage assessed and ten required a combination of ground movement mitigation measures and more precise instrumentation and monitoring equipment (Figure 3).

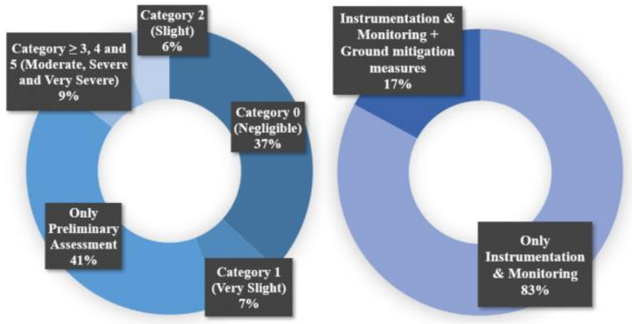

Figure 3. Assessed building damage categories (Burland, 1995) and ground movement mitigation measures.

2.2 Ground movement curves

The ground movements were calculated for each building and along each of its walls. The curves were obtained from bi-dimensional and tri-dimensional finite elements models (FE) (Figure 5). The curves were obtained for surface and sub-surface ground movements (vertical and horizontal).

The FE models were used to design the shaft support, retaining walls and the tunnel primary lining. These included the geotechnical model of the ground, the excavation support, surcharges of adjacent structures and the construction stages. The ground movement curves obtained from the FE models were compared with empirical curves from Peck (1969) and CIRIA 760 for reference.

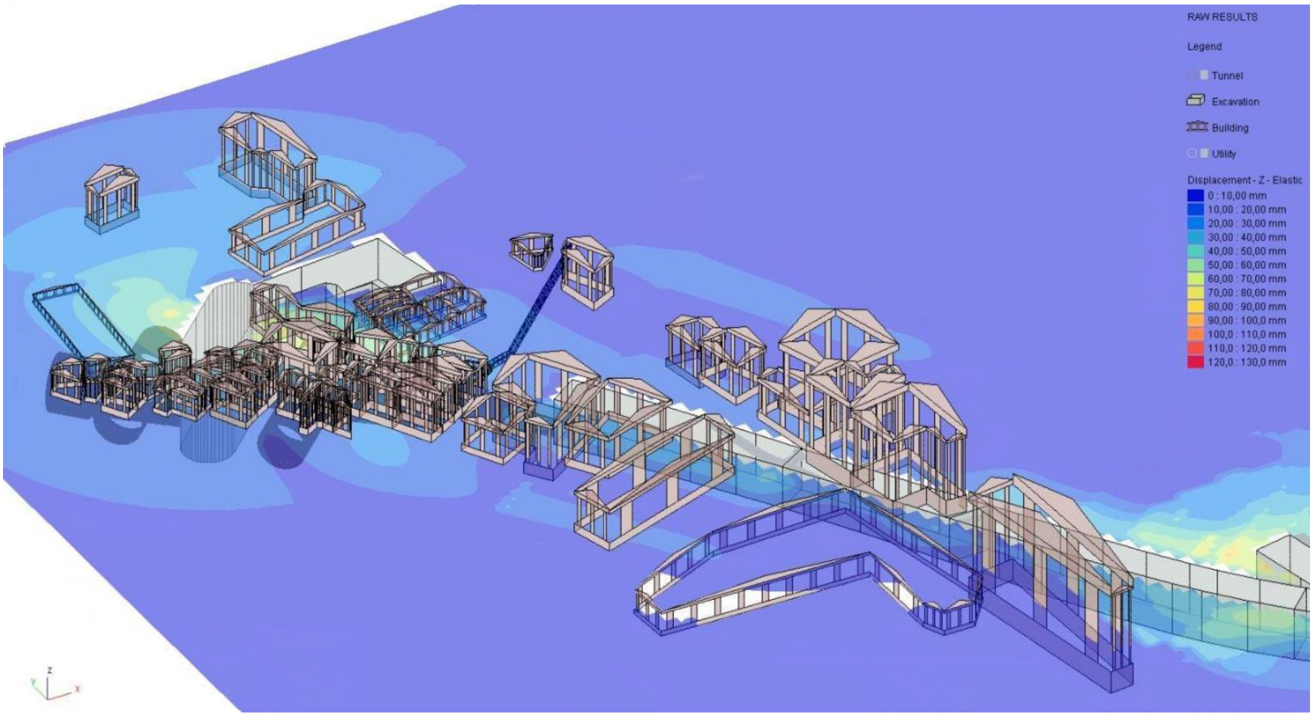

Figure 4. 3D view of the damage assessment model.

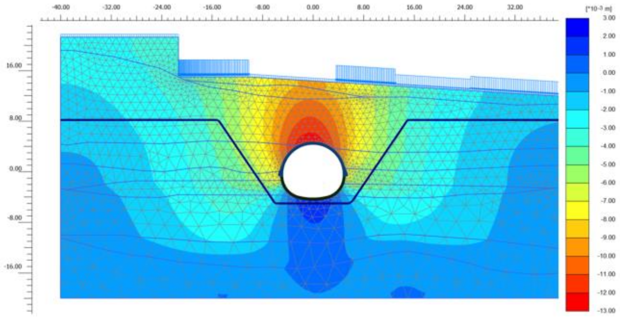

Figure 5. Example of a bi-dimensional finite element model.

2.3 Buildings

To assess damage categories in accordance with Burland's (1995) assessment method, a set of properties were required to be assigned to each building wall. These properties are representative of the building's geometry and the type of structure so that the maximum resulting tensile strains can be calculated and compared to the damage category limits.

In order to consider the vulnerability of listed buildings, the obtained damage category was increased by up to two levels, depending on preexisting damage and architectural features.

3 RESULTS

For the purpose of presenting an example of the building damage assessment work carried-out for this project, the following points describe the results to assess damage on a vulnerable listed building near Santos' station excavation works. Ground movement mitigation measures were implemented in this building to ensure that the resulting damage category was kept within the project's requirement (equal or below Damage Category 2).

3.1 Description of the building

This building was dated to the sixteenth century and it was part of a larger monastery where it was used as a lower choir. Over the centuries this building experienced several modifications to its architecture and to its use. However, the original columns, arches and ceiling paintings are still preserved (Figure 6 and Figure 7).

Figure 6. Low Choir (building's exterior view).

Figure 7. Low Choir (building's interior view) (Left) and Ceiling paintings (right).

3.2 Building damage assessment results

Due to its proximity to Santos' station excavation works, the ground movements estimated at the location of this building were in exceedance of 40 mm (Figure 8).

It was estimated that if no ground mitigation measures were implemented at this building, it could reach damage category 3 (Moderate), and considering the vulnerability of its architectural features, it would reach damage category 5 (Very Severe).

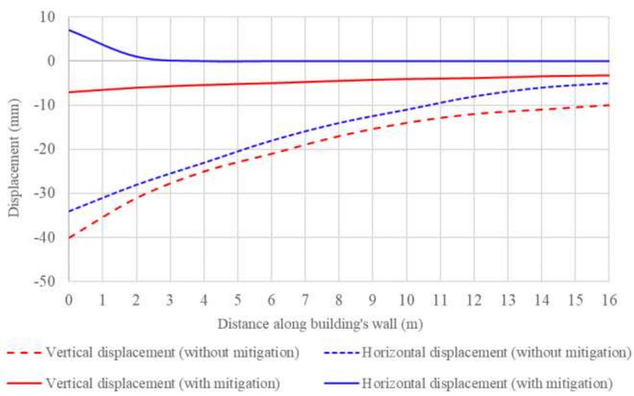

Figure 8. Ground movement profile along the most critical wall (with and without ground movement mitigation measures).

3.3 Ground movement mitigation measures

A desk study was carried-out to determine the most viable, safe and efficient ground movement mitigation measures. It was determined that the measures would be the installation of a ground movement reduction barrier, consisting of a bored piled wall (0,8 metre diameter piles, spaced at 1,0 centres) (Figure 9). and internal bracing of the building's structure (Figure 10).

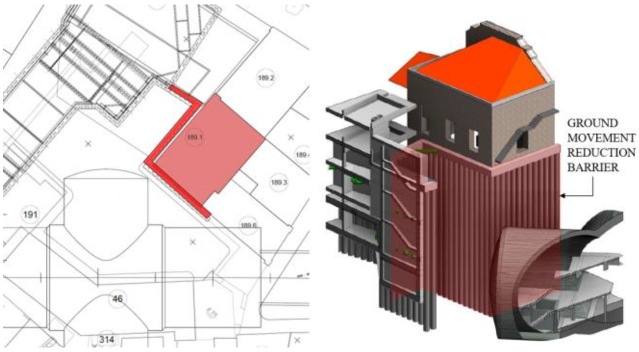

Figure 9. Location of the ground movement barrier.

Figure 10. Internal bracing of the building's structure.

3.4 Assessment of the effectiveness of ground movement mitigation measures

A detailed analysis based on 3D finite element modelling (3D FEM) was carried-out to assess the effectiveness of the ground movement reduction barrier (Figure 11).

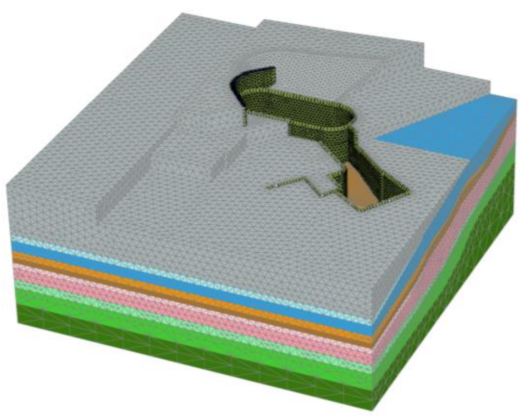

Figure 11. 3D FE model for Santos station (southern side).

The 3D FE model was developed to perform safety check calculations for all identified failure mode mechanisms. In order to reduce the calculation time, Santos station was analysed using two 3D FE models, one 3D FE model for the northern part and another 3D FE model for the southern part of the station. To assess the effectiveness of the ground movement reduction barrier, the southern 3D FE model was used. This model considered the heterogeneity of geological and geotechnical ground conditions, the groundwater conditions, the soil-structure interaction conditions, the construction sequence and the reinforcement elements, such as the primary lining and retaining walls (Figure 12).

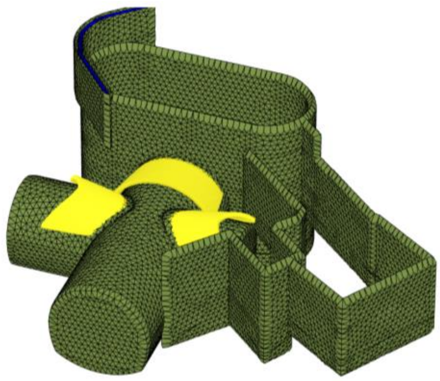

Figure 12. 3D FE model for Santos station (southern side) including primary lining and retaining walls elements.

The ground movement reduction barrier was modelled as a plate element and its stiffness and soil-structure interaction parameters, were assigned accordingly. The presence of the Low Choir building was modelled as a distributed load at ground level. The ground displacements were obtained from the 3D FE model (Figure 13).

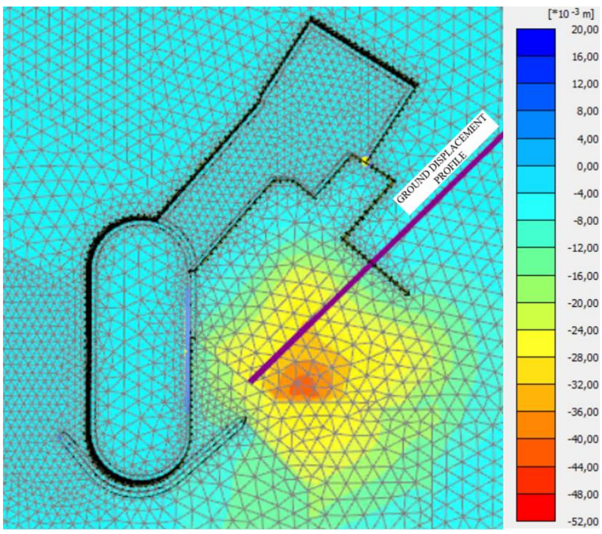

Figure 13. Estimated total displacements with ground movement mitigation measures (3D FEM).

The ground displacements were processed (Figure 14) and its analysis indicated that the inclusion of ground movement mitigations reduced the damage category to category 0 (Negligible), and considering the vulnerability of its architectural features, the damage category was estimated at damage category 2 (Slight).

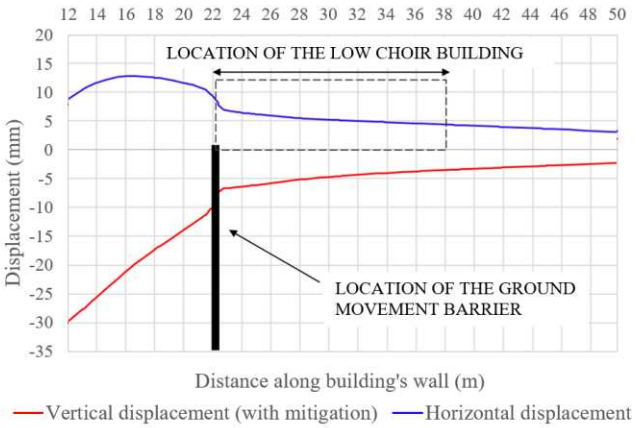

Figure 14. Ground displacement profile with ground movement mitigation measures (ground settlement profile).

4 CONCLUSIONS

This paper provides an overview of the building damage assessment work carried-out to assist the design team on the design of the excavation works for Lot 2 of the extension of the Yellow and Green lines.

The building damage assessment is an essential part of a large infrastructure project including excavation works in an urban environment.

The ability to combine in a damage assessment model multiple sources of ground movement, provides the opportunity to analyse the combined effects of various works. The opportunity to automate this analysis is critical to provide timely input to the design development so that efficient mitigation measures can be introduced, and adjustments can be made to the excavation methodology.

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