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# Effects on Rail and Highway Infrastructures due to Underground Excavations According to Simplified and Detailed 3D Modelling Approaches

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**Abstract.** Tunneling for Metro projects in urban areas has been transformed in an optimal solution because of its minimal impact in the city infrastructure and therefore challenges about predicted models are relevant nowadays. A better understanding of the ground condition and enough settlement monitoring data to calibrate a reliable numerical modelling, can bring accurate estimates of the effects of tunneling on significant infrastructures of the cities. This article presents a comparative analysis considering two different 3D modelling approaches to evaluate the effects on an existing rail and highway infrastructure due to tunneling of a new Metro line in an urban area. The 3D modelling approaches comprise a simplified 3D model considering an orthogonal crossing, between the tunnel and the railway track, using an extrusion technique of the geometry definition program and the other model, the detailed one, represents the actual angle, not perpendicular, of the crossing between the railway and the tunnel. Furthermore, since a highway overpass is part of the analyzed crossing, deformation of its infrastructure was analyzed as well.

**Keywords.** Tunneling, 3D modelling.

## 1. Introduction

According to the International Tunneling and Underground Association [1] the need of underground space has increased in recent years due to land use, isolation considerations, environmental preservation, and topographic reasons. The ground provides a variety of advantages in terms of protection of the environment, such as aesthetics or ecology. These are important aspects related to the design of Metro lines, roads, and different facilities with low environmental impact.

The effects of subsidence due to tunneling on infrastructure in an urban area are relevant for different stakeholders [2-8] and therefore, the challenge is to improve the predicted models about subsidence and infrastructure effects. There are several methods to predict ground movements due to tunneling, from analytic analyses to numerical analyses. Nevertheless, having historic data to calibrate a reliable settlement trough and a deep understanding of the ground condition are worthy to obtain accurate deformation results [9]

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This article presents a comparative analysis considering two different 3D modelling approaches to evaluate the effects on a rail and highway infrastructure due to tunneling of a new Metro line in Santiago de Chile. The new Metro line is located northern Santiago, and correspond to an extension project of the new Line 3 of Santiago Metro, which started its operation early 2019 comprising about 20 km. The extension of Line 3 is a project that comprises 3.3 km of running tunnel and three stations. A plant view of the new Metro line and the crossing allocation are shown in Figure 1.

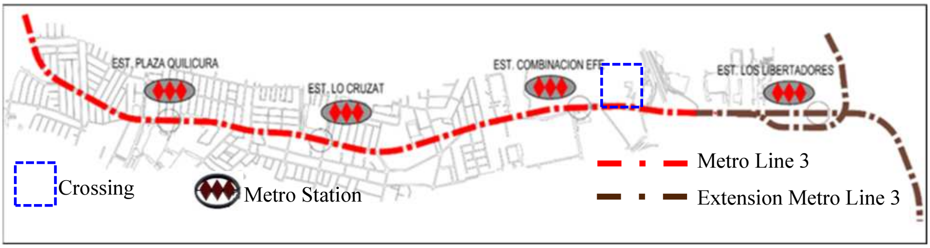


**Figure 1**. Plant view of the new Metro Line.

The complex crossing of this study it is located at the beginning of the extension Metro Line 3 and it is characterized by fine soil, silty clay, and some layers of gravel and sand. The aim of this study is to estimate the railway deformation and the deformations of the overpass highway infrastructure due to the tunneling of the Metro tunnel considering two types of numerical models. A panoramic view of the crossing is shown in Figure 2.

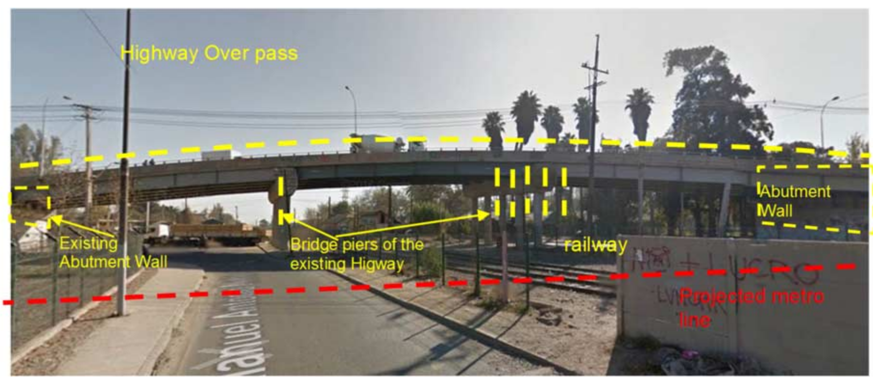


**Figure 2.** Panoramic view of the crossing.

The two 3D modelling approaches comprise a simplified 3D model considering an orthogonal crossing, between the tunnel and the railway track, using an extrusion technique of the geometry definition program and the other model is detailed model that represents the actual angle, not perpendicular, of the crossing between the railway and the tunnel. Furthermore, since a highway overpass is part of the analyzed crossing, differential settlements of its foundations were predicted.

## 2. Ground Condition

The ground condition is characterized by two types of soils at tunnel's depth: Fine Soil (silty clay with sand lenses) and layers of consolidated gravels. Geotechnical parameters of these soils have been determined by laboratory tests and by back analyses with monitoring data [10]. For the numerical analyses both fine soil and gravels were represented by Cap Yield constitutive model [11], which is characterized by a Mohr-Coulomb failure criteria and a non-linear envelope for volumetric change.

The stratigraphic section of the studied zone and the tunnel rail depth are shown in Figure 3. Because of the minimal presence of gravels in comparison to the fine soil, indeed most of the gravel will be excavated for tunneling; the presence of gravels was ignored to build the numerical model, considering a more conservative approach in terms of ground deformation and tunnel lining stresses. There was not presence of underground water in the studied area. The geotechnical parameters are summarized in Table 1.

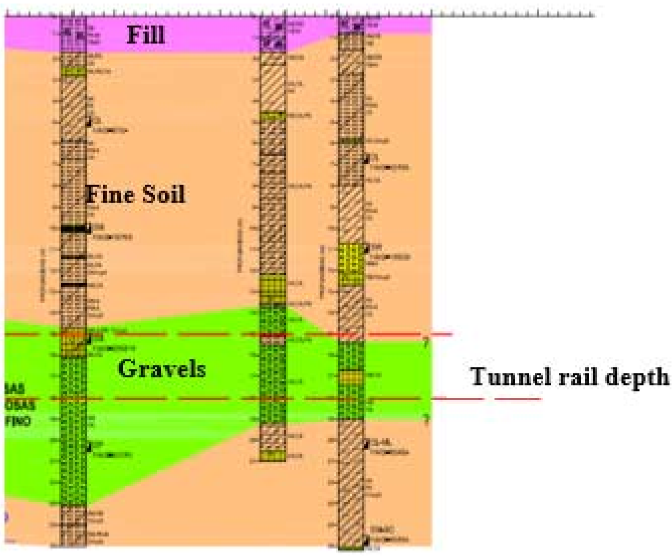


**Figure 3.** Stratigraphic section.

**Table 1.** Geotechnical parameters of fine soils.

| Parameter | Unit | Depth | |
|---|---|---|---|
| | | z ≤ 8 m | z > 8 m |
| Specific Weight | Ton/m$^3$ | 1,85 | 1,85 |
| Elastic Modulus | Ton/m$^2$ | $2000 + 275\,z$ | $2000 + 275\,z$ |
| Poisson Coef. | | 0,3 | 0,3 |
| Cohesion | Ton/m$^2$ | 3 | 5,5 |
| Frictional Angle | ° | 31 | 31 |

One of the important characteristics of the Cap Yield constitutive model is that it simulates the hardening effect of load and unload steps, which is appropriate to unloading cases such as underground excavations.

The Cap-Yield model is based on the Mohr-Coulomb failure criterion and a non-linear response for the volumetric change called Cap-Yield. When material also exhibits a cohesive component, a pseudo-linear first branch followed by the hardening frictional segment is frequently observed [12]. To calibrate the model drained triaxial drained tests were used to obtain the hyperbolic law. This is an adjustment in the different characteristics of the behavior through the selection of the hardening laws, in addition to a stress-strain law similar to the hyperbolic model and the incidence of the stress trajectory in the deformation modulus. Table 2 presents the design parameters for modelling of fine soil [1]. Although, non-linear behavior of the soils is considered for modelling, the concrete is considered as an isotropic linear elastic material.

**Table 2.** Design parameters of fine soils – hardening soil of Extension Metro Line 3 (CY-Soil/Hardening Soil).

| **Parameter** | **Unit** | **Depth** | |
|---|---|---|---|
| | | **z ≤ 8 m** | **z > 8 m** |
| Shear Modulus $G^{e}_{ref}$ | kPa | 35054 | 69260 |
| Volumetric Modulus *Kiso ref* | kPa | 25316,7 | 50020,8 |
| *R* Factor | | 2 | 2 |
| Potencia según material *m* | | 0,7 | 0,7 |
| Poisson at Unload/Load $\nu_{ur}$ | | 0,3 | 0,3 |
| Reference Pressure $p'_{ref}$ | kPa | 55.57 | 172.24 |
| Pressure Ratio *Hz/Vert* $K_{o\,(NC)}$ | | 0,65 | 0,65 |
| Failure Ratio *Rf* | | 0,9 | 0,9 |
| Stress $\sigma$ | | 0 | 0 |
| Cohesion *c* | Ton/m$^2$ | 3 | 5,5 |
| Frictional Angle $\phi$ | ° | 29,4 | 29,4 |
| Dilatancy $\psi$ | ° | 0 | 0 |

## 3. General Concerns

### *3.1. Tunnel Section and Excavation method*

The tunnel involved in the crossing corresponds of a running tunnel of the Extension of Metro Line 3, and comprises about 80 m$^2$. The tunnel is excavated by a conventional excavation method, considering two excavation sections, bench and invert, which are bounded by the tunnel rail depth. The tunnel lining is 45 cm thick and is reinforced by shotcrete and mesh. The tunnel section is shown in Figure 4.

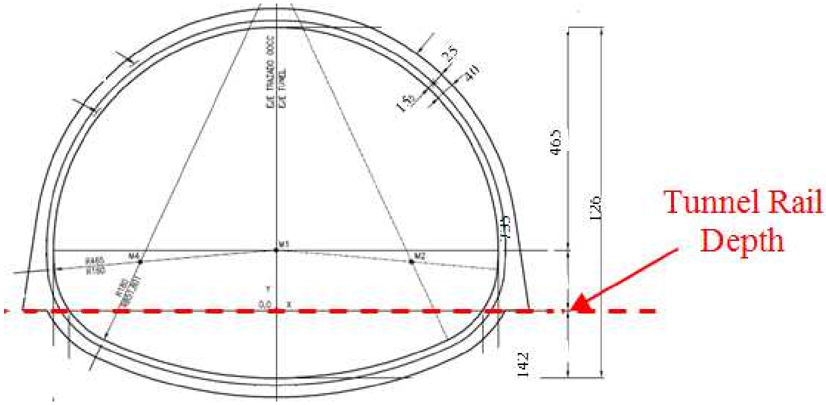


**Figure 4.** Tunnel section.

### *3.2. Problem Description*

The tunnel alignment intersects the railway track at 19 m deep from the surface, where the railway is sited, and the angle between those alignments is approximately 53°. Additionally, there is an existing overpass highway, with an enlargement project of an extra pass way that crosses the railway track with a similar orientation of the tunnel alignment at the crossing. The overpass highway is a bridge formed by reinforced soil walls at the extremes of the crossing that forms the bridge abutments and a series of piers next to each side of the railway. A plan view and a cross section of the crossing is shown in Figure 5.

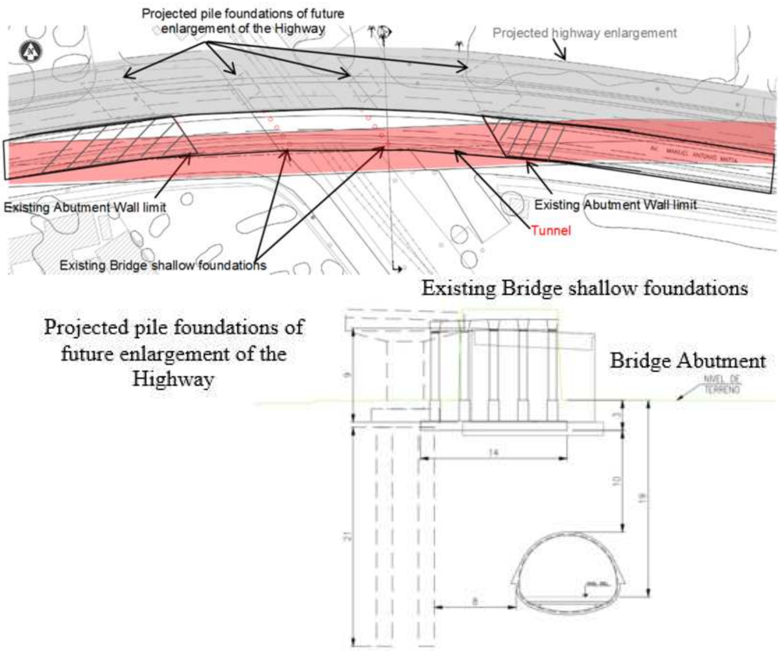


**Figure 5.** Plan View and Cross Section of the crossing.

Basic loads for the different infrastructures are listed in the Table 3. The basic loads were adjusted to the different models and more details are described in section 4.2 of this article.

**Table 3.** Loads of the infrastructure involve at the crossing.

| Load Type | Unit | Load |
|---|---|---|
| Services Load at Bridge Piers of the overpass Highway | kPa | 318 |
| Traffic Loads | kPa | 12 |
| Rail Train | kPa | 50 |
| Bridge Abutments of the New Highway | kPa | 205 |

## 4. Numerical Modelling for the Comparative Analysis

The comparative analysis is based on the results of two different numerical modelling approaches using both FLAC 3D 5.01 version, which is a Finite Difference program.

The first model, shown in Figure 6, corresponds to a simplified modelling, where the crossing between railway and the tunnel is considered perpendicular, because of an extrusive 2D geometry in one direction at certain depth that can generate the geometry/ mesh to obtain the 3D volumes of the structures involved at the crossing. The second model, shown in Figure 7, consist of a detailed 3D modelling, where the crossing angle between the tunnel and railway, the distance between the railroads, the variable height of the highway abutments, and the oblique location of the piers were included.

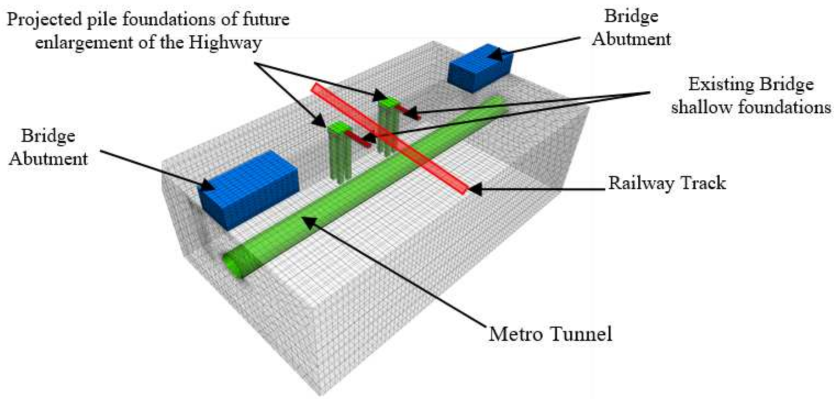


**Figure 6.** Simplified numerical model.

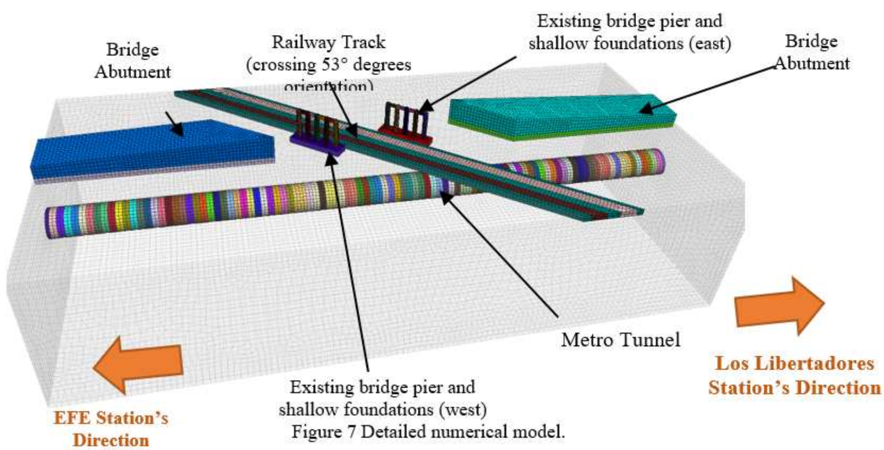


**Figure 7.** Detailed numerical model.

## 4.1. Model Excavation Sequence

The general stages for 3D modelling are listed:

- Initial geostatic analysis. After that, deformations are set.
- Pier and abutments of the overpass highway are incorporated to the model and railway and its equivalent load are included, as well. Then, deformations are set again before tunnel excavation.
- The distance between the bench and invert is maintained at 6 m.

### 4.2. Load Differences between the Models

The rail train load considered for the simplified model considers a train (Cooper E80 model) with a length of 32,7 m and the distance between the steel rails of 3 m, resulting a distributed load of 50 kPa along the railway track . On the other hand, because of extrusion free restrains, the rail train load can be applied in a certain area and also the distance between the steel rails was 3,5 m, that results a train rail load of about 45 kPa and it is applied at the real location of the steel rails.

## 5. Comparative Analysis

The comparative analysis considers the deformations due to tunneling of the different infrastructures involves at the crossing for the different 3D models, i.e. the simplified and the detailed model.

Regarding the railway effects due to tunneling, a specific section to represent the railway track, was evaluated for each 3D model. The Figure 8 presents the section use to compare surface settlements that represents the railway settlements due to the underground excavation of the Metro tunnel.

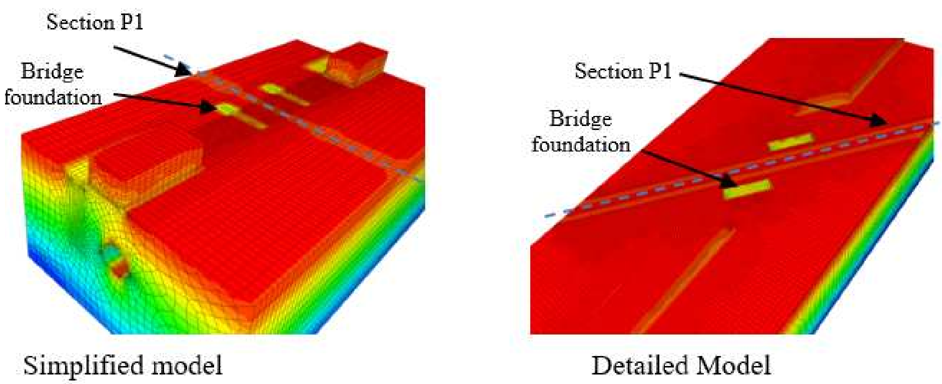


**Figure 8.** Evaluated section P1, along the railway line, to represent the railway track for the different models.

The comparison of the railway settlements due to tunneling between the simplified and the detailed model is shown in Figure 9. It is possible to observe that the maximum settlements are very similar; however, the subsidence zone is larger in the detailed model, probably because of oblique crossing, that represent a greater exposed interference.

Regarding the effects due to tunneling on the highway infrastructures, the comparative analysis was based on the superficial settlements along the tunnel alignment. The different settlement profiles for the longitudinal tunnel alignment considering the different models are shown in Figure 10. It is possible to observe that the settlements of the abutments of the highway in the detailed model are 60% less than the simplified model. This is mainly due to the geometry adjustment of the reinforced soil walls, that the detailed model can decrease the height wall according to the bridge relative distance.

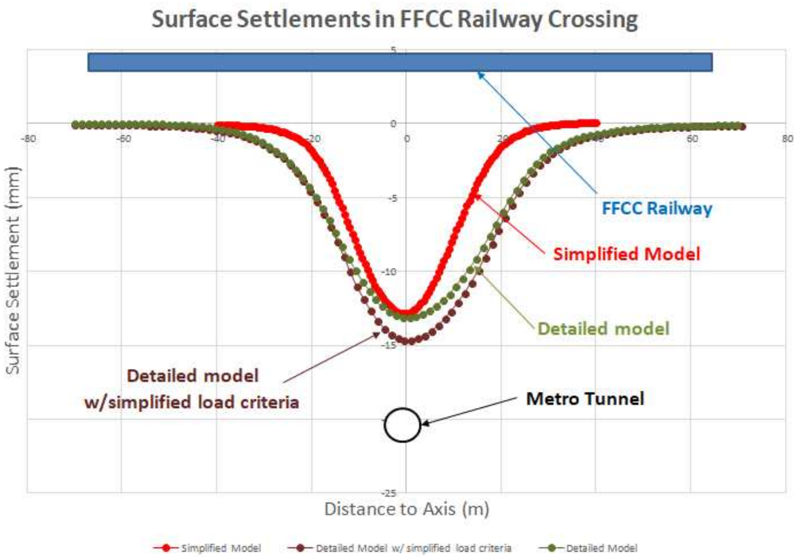


**Figure 9.** Surface Settlements, along the railway line for the simplified and the detailed numerical models.

In terms of magnitudes of settlements at the piers zone, there are similarities between the models and moreover, there are not significant differences between the bridge piers and the maximum predicted settlement could be associated to the detailed model with the simplified bridge load criteria.

Finally, it is possible to observe that the magnitude of the infrastructure settlements due to tunneling are relative minimal, and there are similarities between the 3D modelling approaches.

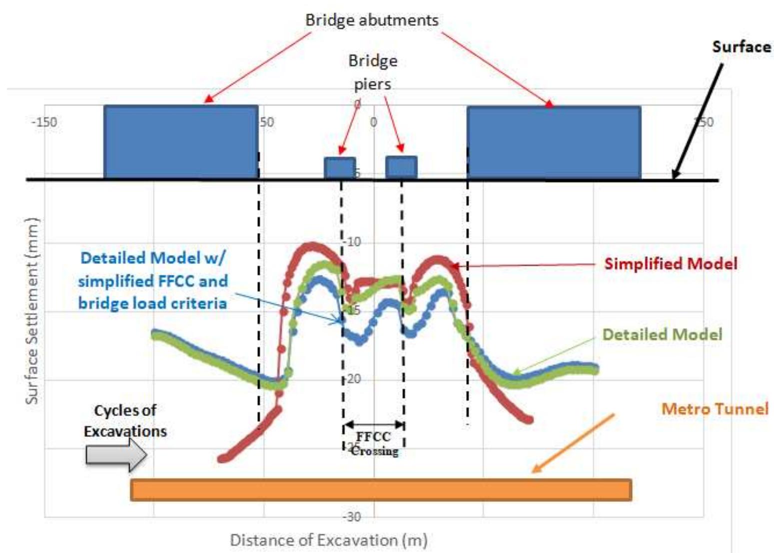


**Figure 10.** Surface settlements in the longitudinal axis for the simplified and the detailed numerical models.

## 6. Conclusions

It is relevant to stay that no matter how sophisticated could be the type of approach to solve a infrastructure deformation assessment due to tunneling, the key factor to achieve accurate results are a deep understanding of ground condition and records of monitoring data to calibrate reliable predicted models.

It is expected to have differences between the deformation results from the simplified and the detailed models, since the geometry of the models are relative different. The key dissimilarities between the models are related to the crossing angle between the tunnel and railway track, the variable height of the wall abutments of the overpass highway, the series of piers orientation regarding the tunnel and finally the load differences because of the simplify model restrains to apply the train loads fundamentally. However, the magnitude to the infrastructure settlements due to tunneling are relative minimal and also most of settlement profiles were relative similar.

Regarding the deformation results of the different infrastructures evaluated, it is possible to conclude that results for the railway deformations and the existing bridge piers of highway are very similar between the simplified and the detailed model. However the size of the subsidence zone, for the railway effects due to tunneling, seems larger in the detailed model. Moreover, there are significant differences (60% less in the detailed model than the simplified model) in the highway reinforced wall, probably due to the variability of height of the wall of the abutment, which was possible to apply in the detailed model.

If the detailed model is loaded with the same criteria than the simplified model the results seems to bring a 15% approximate difference between maximum settlements, and it is possible to conclude that for conditions of an angled crossing around 45° to 55° degrees it is possible to expect settlements 15% bigger if the analysis are made with an simplified orthogonal numerical model, so it is reasonable to considerer that geometry effects can affect the results in a 15%.

Finally, a monitoring program was recommended in order to have a settlement control, comparative analyses with the predicted deformations, and to minimize the impact of the tunneling works.

## Acknowledgements

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