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## **Tunnelling effects on UNESCO World Heritage: the Sagrada Familia case**

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### ABSTRACT

A controversial issue regarding the construction of tunnels in urban areas is the effect on surrounding buildings and structures. The problem is exacerbated when the potentially affected structures are part of UNESCO World Heritage Sites. This is the case of the Temple of the Sagrada Familia and Casa Milà, by the famous architect Antonio Gaudí, in Barcelona, Spain. The paper presents the actions carried out in these buildings to preserve them from the effects of the construction of the railway tunnel for the high-speed line Madrid – Barcelona - French Border.

### 1 INTRODUCTION

The Madrid-Barcelona-French Border Line High-Speed Tunnel runs through the city of Barcelona connecting the Sants and Sagrera stations. It is a 5.664 Km long tunnel, mostly built by a single EPB shield machine. At both ends of the tunnel, cut-and-cover sections were designed to connect to the stations and act as EPB assembly and disassembly shafts.

Figure 1 shows a plan view of Barcelona, with the tunnel axis along Provenza and Mallorca streets, and Figure 2 a longitudinal profile, with the location of the Sagrada Familia Temple and Casa Milà. The article focuses on the Temple of the Sagrada Familia. The same preventive measures were adopted for Casa Milà, and are not included for the sake brevity.

Sagrada Familia Temple occupies a large block on Mallorca street (see Figure 1). It is an “expiatory” church, financed by private donations. Its construction began in 1882 and is still continuing. In 1883 Gaudí was appointed director of the construction works, changing the original design, which was neo-Gothic, to modernist (art nouveau) style. After Gaudí’s death in 1926, his close collaborators continued the construction. In 1936, at the beginning of the Spanish Civil War, an arson attack destroyed most of the drawings. The plaster models survived and they have been used ever since then to interpret Gaudí’s design.

The parts built by Gaudí are the crypt, the apse and the “Nativity” façade. The façade facing Mallorca street is the “Gloria” façade, which was started in 2002 and not yet been completed.

The EPB tunnel is a precast reinforced concrete 11.475 m external diameter lining. Seven segments (6 + key) 0.38 m thick form the lining. The overburden is about 25 m above the crown. The tunnel cross-section is shown in Figure 3.



Figure 1. Plan view of the tunnel and the Sagrada Família Temple

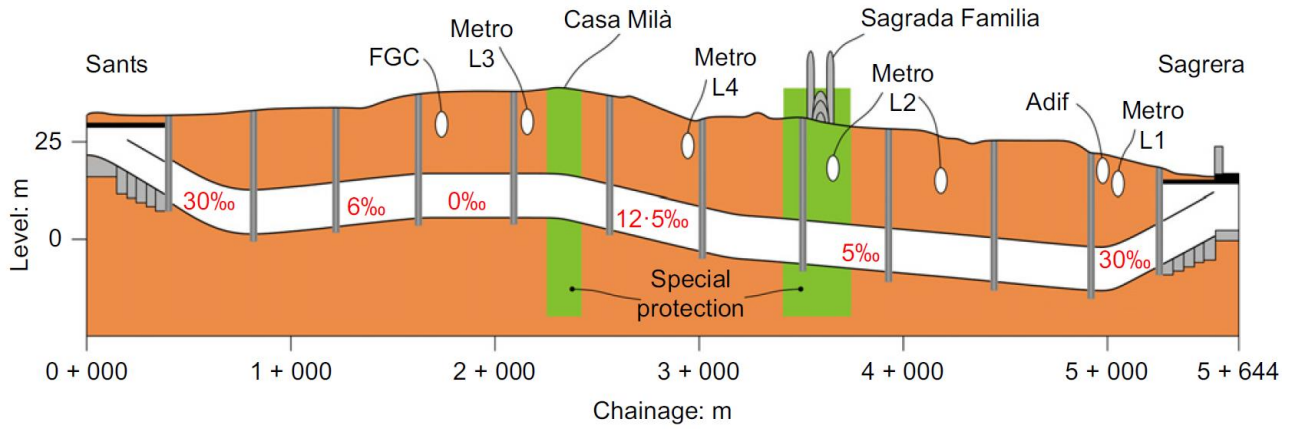


Figure 2. Longitudinal profile of the tunnel

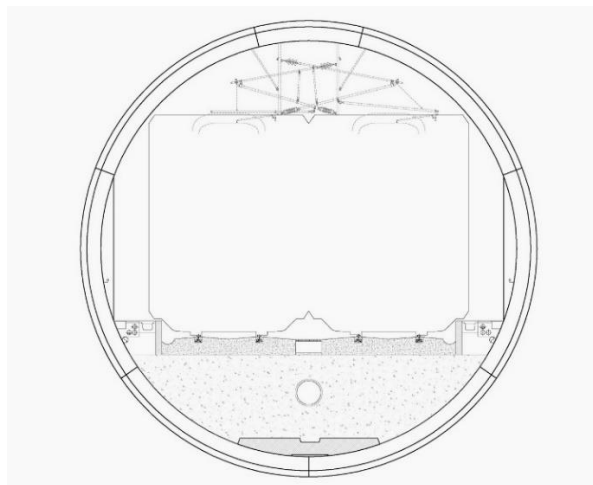


Figure 3. Tunnel cross-section

### 3 THE SOIL

The geotechnical characteristics of the soil near the Sagrada Familia Temple are extensively described in Alonso and Ledesma (2014, 2015) and Ledesma and Alonso (2017).

The geotechnical profile of the soil near the Sagrada Familia is shown in Figure 4. The tunnel is excavated in a stiff Pliocene substratum described as an irregular sequence of sandy clay and clayey sand. Standard penetration test counts varied from 40 to 50, indicating that this is a strong material. A sequence of silts, sands and clays, including some gravels and carbonate concretions, was deposited on top of this layer. These soils are stiff materials, which make a good base for shallow foundations (all the old buildings along the tunnel axis have very shallow foundations).

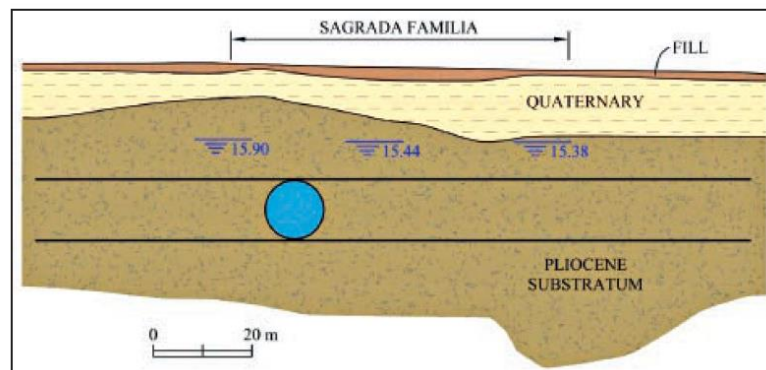


Figure 4. Geotechnical profile near to Sagrada Familia

Water level is located 15-16 m deep. The average water pressure on the tunnel spring line is about 150 kPa (Pujades et al., 2014).

### 4 GLORIA FAÇADE PROTECTION

Figure 5 (left) shows a schematic cross-section of the Sagrada Familia foundations that support the Gloria façade and the columns of the main church nave. It also shows the position of the tunnel and the first idea to protect the Temple.

It is important to highlight that the Gloria façade and the main church nave are modern structures, with a well-designed deep foundation with piles and pile caps. The old part of the temple, which is Gaudi's original, with a poorer foundation, is away from the tunnel.

The first idea to protect the Temple was to construct a jet-grouting enclosure prior to tunnel excavation and it was planned that the EPB would bore through this jet-grouting block. There was a concern that the displacements induced by the jet-grouting itself, during its injection, would affect the Temple. It was therefore discarded.

The protection finally adopted is shown in Figure 5 (right). A pile wall was built between the tunnel and the Sagrada Familia foundation, with 1.5 m diameter piles spaced 2.0 m apart and 41 m deep. The pile heads are connected by a pile cap. To reduce the lateral displacements of the pile cap, a large concrete block was connected to the pile cap beam. The distance between the axis of the pile wall and the Sagrada Familia façade was 2 m. The spacing between the piles allows the free passage of water, avoiding any effect on the natural groundwater flow. Analyses indicated that the tunnel did not constitute a significant barrier to flow, due to the high permeability of the sandy layer. Details of the groundwater analyses are described by Pujades et al. (2014, 2015).

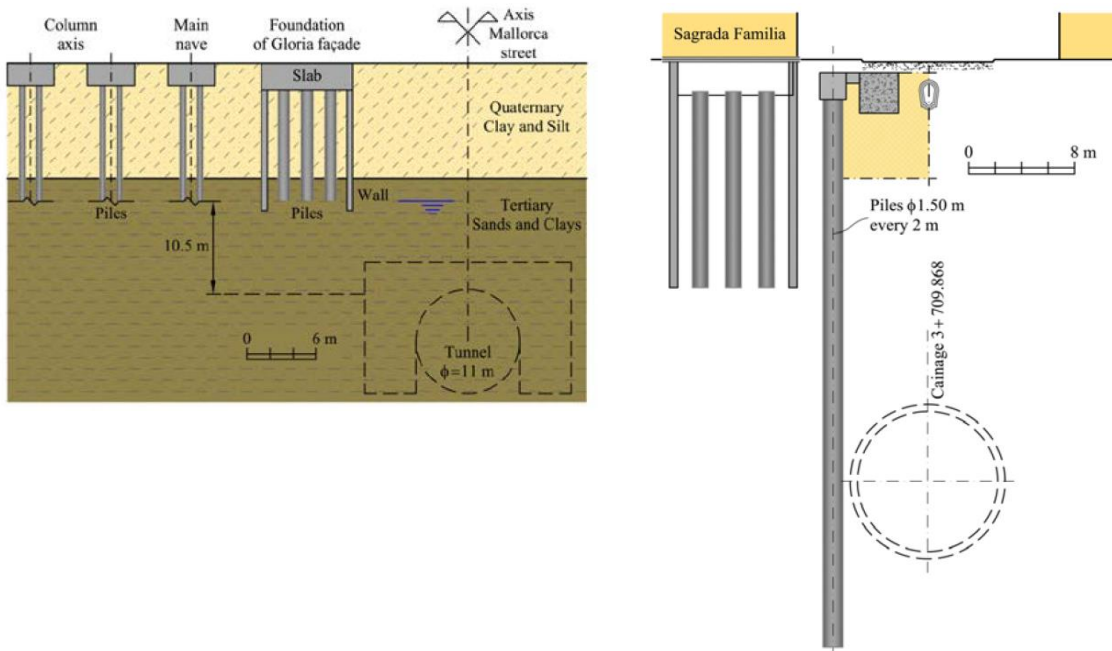


Figure 5. Initial proposal for the tunnel in front of the Gloria Façade (left) and adopted solution (right)

The use of pile walls to protect buildings against tunnel settlements is widespread. Some examples can be seen in Alonso and Ledesma (2014), including an earlier one in Barcelona during tunnelling of metro Line 9. Analytical solutions to obtain the interaction between the tunnel construction and the building foundation are also extensively explained in the cited reference.

Figure 6 shows an estimate of how a protecting wall would affect the settlement trough at the Gloria façade using these analytical methods for a volume loss of 0.5%, which was obtained in previous tunnels in Barcelona in the same Tertiary formations. The maximum settlement at the tunnel crown increases, but the settlements behind the pile wall are drastically reduced, protecting the existing building.

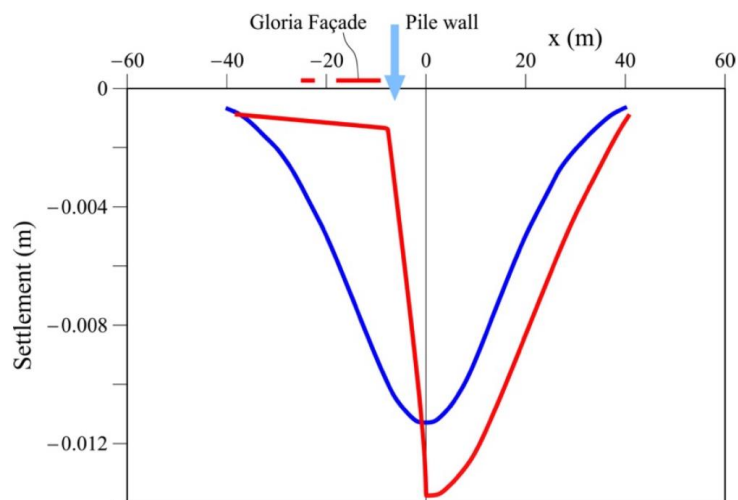


Figure 6. Analytically calculated settlements excerpted from Alonso and Ledesma (2014)

This vertical settlement prediction was combined with a horizontal displacement prediction at the surface in a green field scenario. Thus, a safe estimate of façade damage could be obtained from Boscardin-Cording (1989) diagram. The results obtained were that the damage would be negligible with a volume loss of 0.5%. From this starting point, FEM models were developed to confirm these hypotheses.

## 5 THE TEMPLE

### 5.1 Modelling

The interaction between the tunnel and the foundations was modeled using a 3D finite difference software. The Sagrada Familia itself was modeled by a FEM software (Figure 7), using linear elastic elements. Details on the models are explained in Rodriguez and Blanco (2012). Other models with geotechnical finite element software were also developed (Alonso and Ledesma, 2022).

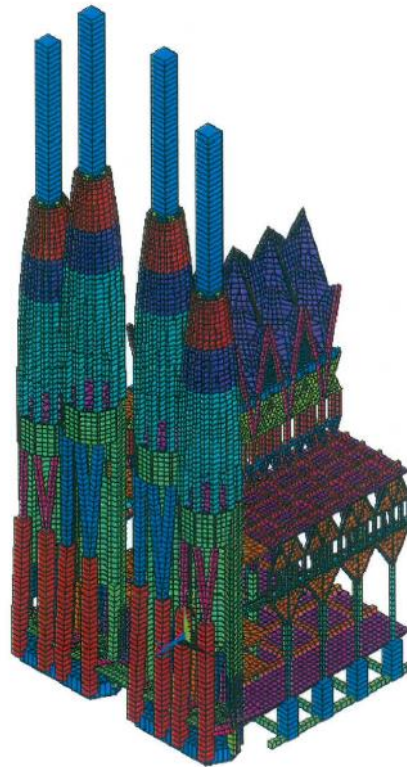


Figure 7. FEM Model of the Gloria façade (Rodriguez and Blanco, 2012)

### 5.2 Monitoring

Monitoring included the Temple, the tunnel lining and the ground around both. Ground monitoring included leveling marks, rod extensometers, incremental extensometers, inclinometers and piezometers (Figure 8).

Crack monitoring of the Temple included displacement transducers, fibre optic extensometers and traditional crack monitors. Displacements were measured with cable extensometers, optical extensometers, leveling marks, ... Vibrations induced by tunnelling were measured by accelerometers.

Finally, weather conditions, such as wind speed, wind direction and temperature, were also recorded.

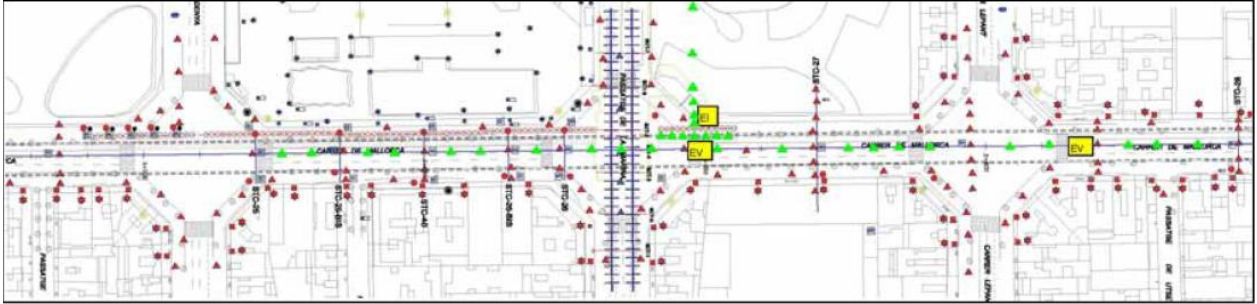


Figure 8. Plan view of the ground monitoring



Figure 9. Monitoring of the displacements inside the Temple (robotic theodolite on the left and target placement on the right)

## 6 THE CONSTRUCTION

### 6.1 Pile Wall

As shown in Figure 5, the pile wall was designed at a distance of only 0.76 m from the tunnel lining. Also, the distance between piles was only 0.50 m, when their length was 41 m. Therefore, verticality was a very important issue. In addition, because the pile wall was so close to the Gloria façade, vibrations during drilling could also generate cracking in the structure.

The construction of the pile wall (Figure 10) began at the end of the wall furthest from the Temple. Thus, it was possible to measure the vibrations and displacements induced in the soil, confirm the soil strata, check the verticality by ultrasonic techniques and verify the integrity using cross-hole tests. After these first piles, the construction method was validated.

Displacements induced in the Temple foundation during construction of the pile wall were negligible and within the error range of the monitoring.



Figure 10. Pile Wall construction in front of Glory Façade

## 6.2 Tunnelling

During the tunnel passage, all the monitoring was continuously measuring all the parameters. Figure 14 shows the settlements in the center of the Gloria façade. The computed settlements correspond to a volume loss of 0.5%, whereas measured ones represented a volume loss of approximately 0.04%.

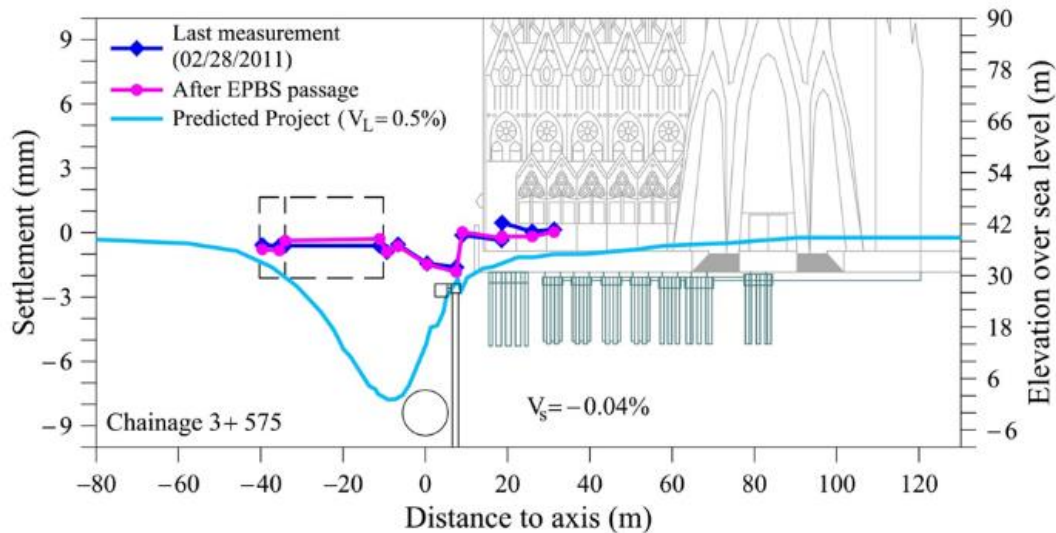


Figure 11. Measured and computed vertical displacements due to the tunnel excavation.

Thus, the maximum displacements measured were only about 2 mm above the tunnel crown, which is about 1/10 of the thermal movements of the Temple. Behind the wall, most of the movements were below the accuracy range of the measuring instruments used, being completely negligible. No new cracks or variation in the width of existing cracks were noticed.

The figure also compares post-passage and long-term settlements. No long-term settlements were observed.

The effect of the pile wall was clear, drastically reducing the settlements behind them, proving to be a very good technique to reduce the settlements of the Temple.

## 7 CONCLUSIONS

The paper explains a successful experience on the reduction and control of settlement due to tunnelling in historic buildings, such as the Sagrada Familia Temple, which is a UNESCO World Heritage building.

Analytical calculations were used to pre-design a pile wall to protect the Gloria Façade from settlement induced by EPB tunnelling. The design was then confirmed by several FEM models of the tunnel, the protection and the Temple.

The paper also presents the monitoring of the Temple and tunnel and the final settlements obtained and their comparison with theoretical ones.

In addition to the pile wall protection, it was also important to reduce the volume loss of the EPB (to only 0.04%) by closely controlling all EPB parameters (which were optimized during tunnel excavation before reaching to the Temple by monitoring). The cutterhead was inspected and repaired in a shaft one block away from the Temple before the passage.

## 8 ACKNOWLEDGMENTS

The authors participated as structural advisors during the construction and Prof. Ramos was a member of the UNESCO Board of Experts. Many engineers were involved in the project, in particular those from ADIF (Spanish Railway Infrastructure Agency), Sacyr – Cavosa – Scrinser (main contractor), Intecsa – Inarsa – Censa design team, Sener (EPB online external control unit), Intemac (Monitoring, inspection and modelling), colleagues from UPC-BarcelonaTECH, and members of the Board. The success of the project is the result of the effort and dedication of all of them.

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