Examples of preserving historic buildings from the impact of tunnelling

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ABSTRACT

The construction of the high-speed railway line from Barcelona to the French border, involved the excavation of tunnels crossing the central districts of the cities of Barcelona and Girona. Some historic buildings were potentially affected by the excavations and a great effort was made to reduce that impact as much as possible. The lecture presents 3 cases of very different buildings and the corresponding Geotechnical Engineering solutions adopted: an old farm house from 12th century, where an underpinning system was designed; the building "La Farinera", from early 20th century, where a compensation grouting was carried out, and the Sagrada Familia Basilica, where a barrier of stiff piles was built to protect the world heritage monument from the tunnel. Preserving those monuments was one of the main challenges of the whole project. The impact of the tunnel on them was negligible thanks to an elaborated design and to the tight control during construction. On the one hand, the design involved the use of 2D and 3D finite element analyses, using advanced constitutive models considering the soil stiffness at low strains and performing an intense site investigation. On the other hand, the control of the tunnel boring machine was intense as well, with an independent external team replicating and checking the operations of the driving team inside the TBM. Overall, it is a good example of how to carry out large and complex construction projects while respecting the heritage of historic buildings. Finally, some learned lessons and future challenges are described.
Keywords: Tunnelling, settlements, small strains, protective barrier, compensation grouting.

INTRODUCTION

The evolution of historic cities nowadays implies the construction of infrastructures that in many cases involves tunnelling or large excavations developing the underground space. Inevitably, there might be a conflict between progress and preservation of cultural heritage, and therefore, an important effort should be carried out by Geotechnical Engineers to overcome that apparent clash. In the past, the control of settlements due to tunnelling was very limited and several cases have been described where this conflict became important (Bezrodny et al., 2016; Moormann, 2026). Despite the progress in the last 50 years in the design and modelling procedures and in the construction techniques, this conflict still remains and any interaction between an underground construction and a historic building is still a challenge for geotechnical engineers (Viggiani, 2024). Conversely, the construction of tunnels in historic cities preserves their buildings and existing heritage above ground from the effects of traffic congestion and degradation of the surface space (Broere, 2016).

This paper presents the experience of three historic constructions affected by a tunnel excavation in the context of the project of a new high speed railway line between Barcelona and the French border. Each case corresponds to a different type of protected building and the solutions considered to reduce the tunnel impact are different as well. Regarding the tunnel, the main construction works were finished by 2014, allowing the circulation of trains from Barcelona to Paris, although some of the structures for railway stations are still under construction nowadays.

LAYOUT OF THE RAILWAY LINE

The high speed railway line connecting Barcelona with the French border involved the construction of a tunnel crossing a central district of Barcelona, the “Eixample” or the Extension district, an area that was developed during mid-19th century and beginning of 20th century, with many “art nouveau” buildings that are classified or protected as world heritage constructions. Most of the tunnel was designed to follow streets, to avoid passing below existing buildings, but its impact on nearby structures was a concern. The railway line continues from Barcelona towards the North to the city of Girona, 100 km away. Another tunnel was planned to cross that city below existing modern buildings, although one of them was historic and required special attention.

This paper presents 3 different examples of interaction between historic buildings and tunnelling, considering a different preserving technique for each one. The decision of which technique is more appropriate depends on several conditions: type and importance of building, expected impact typically in terms of induced displacements, future use of the area and the building itself. The first case corresponds to an old farmhouse (“Torre del Fang”) with little historic importance, but that was preserved because of the municipal interest in creating premises for future public use by neighbours. The tunnel was planned below the building, with a very low cover, so the impact was strong. The second case corresponds to a historic building designed for a flour factory in 1910, but now used as headquarters of a local newspaper. The tunnel was planned just below the building, but with enough cover to design a compensation grouting. Finally, the third case corresponds to a world heritage basilica, a singular building very sensitive to movements. In that case the tunnel was planned parallel to the façade so the expected impact was limited. Each case shows different implications in terms of historic value and risk of tunnel impact.

THE “TORRE DEL FANG” BUILDING

It is a medieval farmhouse, some studies date it back to the 12th century, linked to the Barcelona county and surrounded at that time by agricultural land. Nowadays it is in an area still affected by the construction of “La Sagrera” high-speed railway station, in Barcelona, and the building is in a very poor state waiting for a decision on its use when works are finished. The original construction was made of masonry stone blocks, but the additions during 15th century were made of masonry and a mud mortar (the Catalan word “fang” means mud). The north portal of the tunnel connecting Barcelona with the French border was designed next to that farmhouse, because there was enough space to assemble the TBM machine for the tunnel construction. Figure 1 shows a front view of the building and a rear view with the TBM being assembled. A cut and cover technique and an underpinning scheme were designed to protect the farmhouse as the tunnel was planned just below the foundations of the building. Figure 2 shows a plan view of the building and the tunnel. The construction steps were defined as follows:

- Boarding up the windows to provide stiffness to the building walls.
- Temporary lowering of the groundwater table.
- Construction of a diaphragm wall 0.8 m thick at each side of the tunnel except in the area close to the building, using hydraulic grabs.
- Construction of a secant pile wall 1.2 m in diameter, close to the building.
- Construction of micropiles, 250 mm in diameter, inside the building, to complete the walls in the areas covered by the building itself.
- Construction of micropiles, 250 mm in diameter, as a foundation of a perimeter tying concrete beam surrounding the masonry walls of the building.
- Construction of the perimeter tying beam attached to the building walls and prestressing of the bars to connect the perimeter beam to the building masonry walls.
- Construction of 4 concrete post-tensioned beams to support the upper slabs of the tunnel.
- Construction of upper concrete slabs by segments.
- Post-tensioning of the 4 concrete beams.
- Excavation below the upper slabs by zones. In the area laterally protected by micropiles, construction of segments of an additional concrete wall while excavating.
- Dismantling of the perimeter concrete tying beam and the prestressing bars.

Figure 3 presents the soil profile in the area. Note that water table was about 13 m depth and therefore most of the excavation was under unsaturated conditions, which is convenient as soil stiffness and soil shear strength increases with unsaturation. However, pumping wells were designed to reduce the ground water table below the excavation level, at the bottom of the tunnel. The oedometric modulus was estimated between 60 and 80 MPa for the clay around 10 to 15 m depth, corresponding to SPT blows about 25 to 40 and pressurometer modulus from 11 to 20 MPa. Pumping did not generate significant settlements, as the Barcelona red clay is slightly overconsolidated, because water table was even lower in the past. After the works, measured displacements were below 5 mm in the Torre del Fang and well below that value in the buildings of the surrounding area.

In this project some particular values for the maximum expected settlements were adopted for each area or even for each building. Yellow warnings and red alarm warnings were defined and a protocol was established for each situation. In this particular case, maximum settlement in the historic building was limited to 10 mm for a yellow warning and to 15 mm for a red one. These values were defined considering the current state of the building, quite poor, and that a final retrofitting when finishing the works should be carried out. In fact, the corresponding limits for residential buildings in the area (reinforced concrete structures) were smaller, defined as 9 mm for yellow and 13.5 mm for red warning. Monitoring of building displacements was continuous using robotized surveying, and thermal effects were even more important than displacements due to the construction. A reference target in a deep borehole, and targets in buildings outside the working area, were used to distinguish the effect of temperature from the impact of tunnel.

Prediction of displacements of the historic building due to the excavation was quite difficult, due to the complexity of the operations involved. Simplified analyses using software Plaxis 2D (Brinkgreve et al., 2011) and the Hardening Soil model were carried out. In any case, an effort was devoted to minimize the impact of tunneling, thanks to the construction of the perimeter tying beam, that supported the overall building. The simplicity of the building interior partitions was an advantage, and the control of forces in the post-tensioned beams was able to uplift part of the building if required. Regarding long-term conditions, the fact that part of the building was resting on natural soil and part on the tunnel, could lead to differential settlements. Additionally, any reduction of water table in the future could generate differential settlements as well. That should be considered when retrofitting the building in the future. This example constitutes a case of strong impact of the tunnel on the historic construction.

THE “FARINERA” BUILDING

This case refers to the interaction between a tunnel and a historic building called “La Farinera”. It is located in the city of Girona, 100 km north of Barcelona and designed in 1910 in “Noucentisme” style (a movement that developed as an alternative to Modernism) by architect Rafael Masó Valentí. The building underwent several renovations in the last 50 years, but always keeping the style at least in the façade (Figure 4).

The tunnel layout was passing about 14 m below that masonry building and below other modern reinforced concrete buildings. The tunnel was 12.11 m in outer diameter and was excavated by means of an Earth Pressure Balanced Shield (EPBS). A compensation grouting scheme was designed to reduce the influence of the tunnel on those buildings, in particular, to reduce the impact on the historic construction, more sensitive to settlements (de Santos and Ledesma, 2015).

Figure 1. *Left: Front view of the “Torre del Fang” building. Right: Rear view of the building with the tunnel and the assembling of the TBM.*

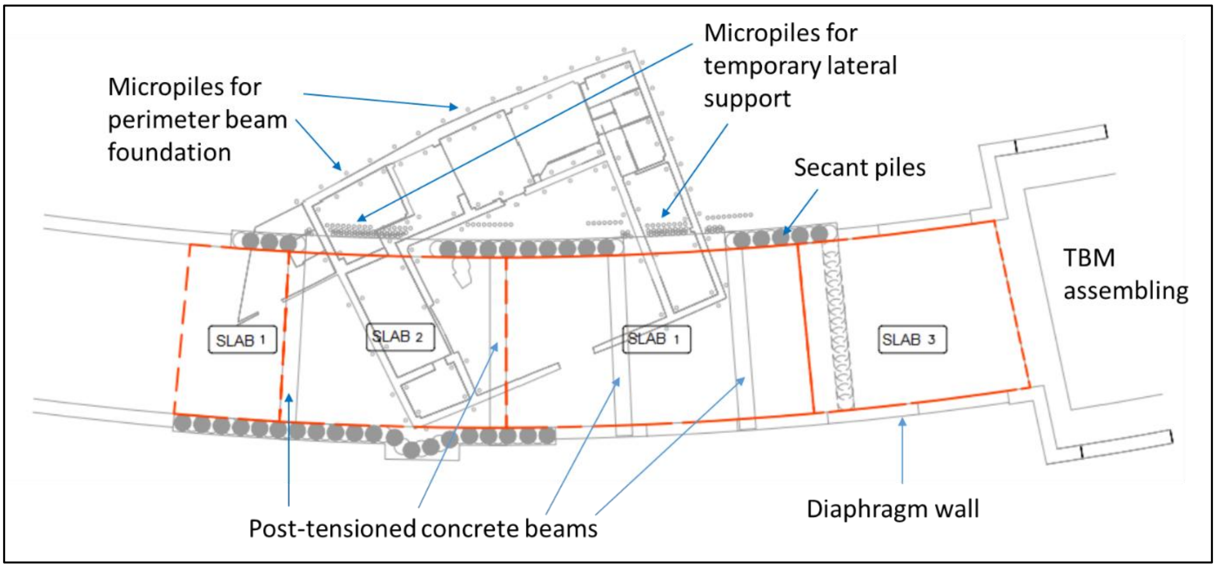

Figure 2. *Plan view of the tunnel and the building, indicating the construction elements involved.*

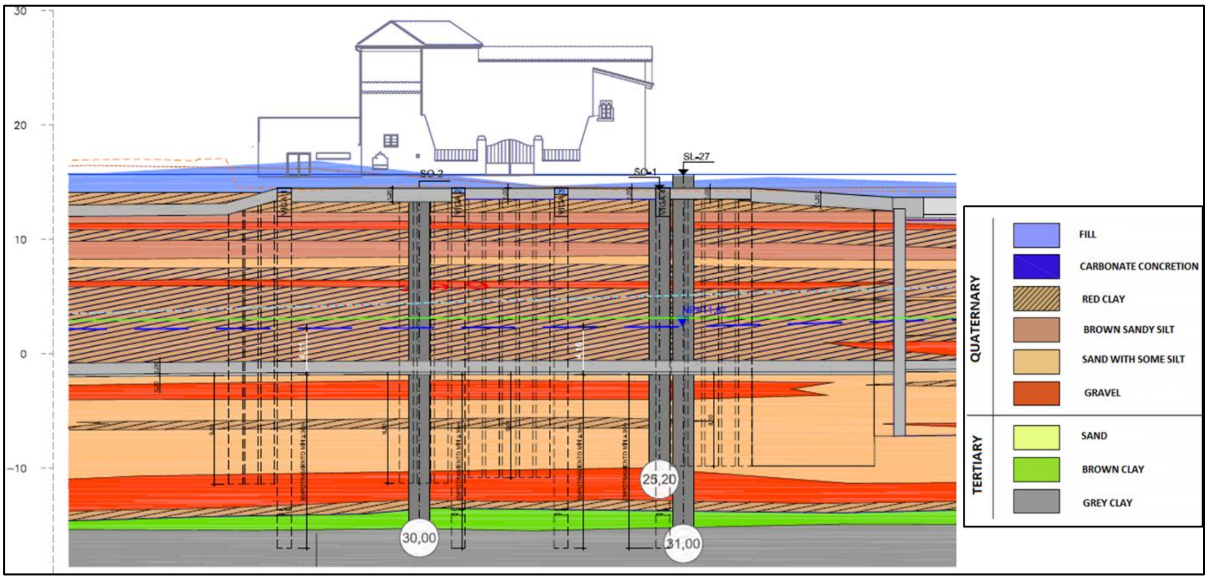

Figure 3. *Soil profile below "Torre del Fang". TBM assembling area is on the right of the Figure.*

Figure 4. *General view of the "Farinera" building from Santa Eugènia street*

Figure 5 shows a plan view with the location of a vertical shaft positioned in an internal passage from which it was possible to drill and install the injection pipes. Those operations did generate negligible movements on the buildings, an aspect that may be important in general.

It is worth mentioning that “La Farinera” building was expanded including basements for parking purposes, using reinforced concrete, except below the main original building. That structural configuration was particularly complex regarding the potential influence of settlements due to the tunnel construction and the displacements generated by the grouting itself. Numerical calculations carried out using FLAC3D, previous to construction, suggested a maximum settlement of 17 mm at the foundation level whereas from a structural point of view, the limit value proposed for the historic building was 7 mm (Intecsa-Inarsa, 2009). Although the value of 17 mm corresponded to the worst scenario and the experience with the EPBS in previous sections was very positive, a compensation grouting plan was developed to reduce the risk of affecting the building above the tunnel.

Figure 6 shows the basic soil profile in the area. The main soil unit in this case corresponds to a slightly overconsolidated clay (Ko coefficient of about 0.8). On the one side, a 3D structural analysis of the building was carried out using SAP2000 (Ramos, 2011), to analyze the sensitivity of the building to differential settlements. On the other side, a 3D geotechnical model was developed using PLAXIS 3D, to reproduce the effect of the compensation grouting and the tunnel excavation. Nowadays it is a standard practice to analyze this geotechnical-structural interaction in a decoupled manner. The development of single numerical codes solving both problems simultaneously is still a current research topic and it is discussed below. Regarding the geotechnical problem, details of the models and the parameters involved can be found in de Santos and Ledesma (2015). A 3D geometry was considered in order to take into account the obliquity of the tunnel with respect to the buildings. The Hardening Soil Model was used for the Pliocene materials and the Mohr-Coulomb model for the Alluvial and the Fill.

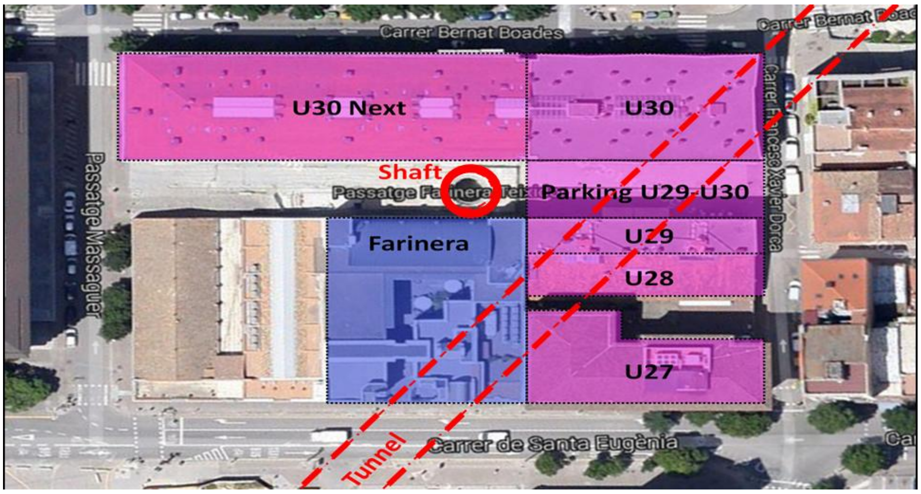

Figure 5. *Plan view of the buildings included in the compensation grouting activities*

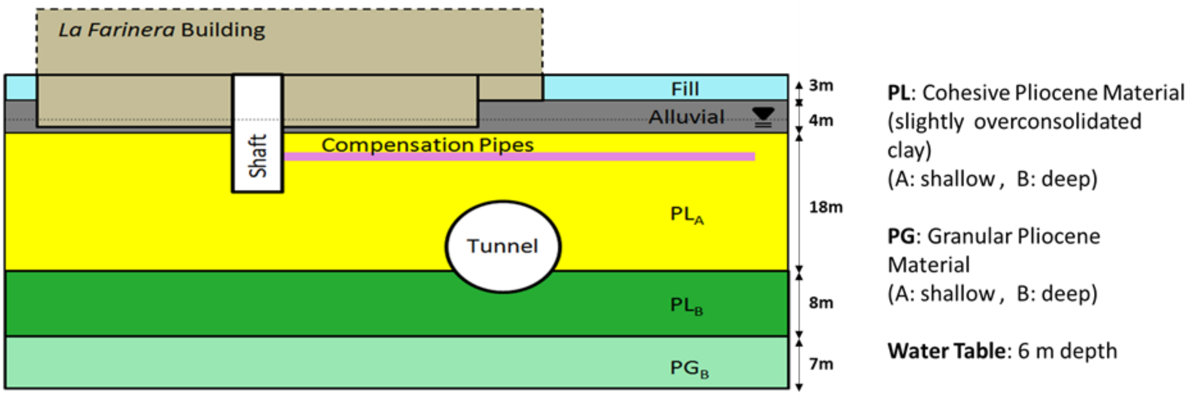

Figure 6. *Basic soil profile and geometry of the zone involved in the compensation grouting operations*

The structural elements above ground were considered in a simplified manner. Buildings U27, U28, U29 and U30 (Figure 5) were simulated as solid volumes with the required density to apply the actual weight to the foundation level. Building “La Farinera” was considered by means of structural plate elements for the basements and with vertical loads for the elements above ground. The objective of the geotechnical PLAXIS 3D model was to evaluate the distribution of movements to be applied as input data on the structural SAP2000 model.

The compensation grouting procedure involves typically 3 stages: i) a preconditioning stage with two phases, first injection without causing movements and a second phase inducing a small uplift of the ground level; ii) a compensation stage during tunnel excavation if settlements larger than a limit value (i.e., 5 mm) are generated and iii) a post-treatment stage in case consolidation settlements occur. These 3 stages should be considered in the simulation analyses and there are several strategies to cope with that (Schweiger et al, 2004; Wisser et al, 2005). In this case, the finite elements of the model around the compensation pipes were directly defined as grouted material, thus representing from the beginning the first phase of the pre-conditioning stage. Then, the second phase was simulated by applying a fixed volumetric strain to the grouted elements of 0.54%, based on the measured injected volumes of grout in that phase well before the tunnel excavation. A maximum uplift of 4.4 mm was obtained in the model in “La Farinera” building.

It is obvious that this type of works requires an intense and continuous monitoring of the soil, buildings and facilities nearby. Measured displacements in the uplift phase of the first stage were about 2 to 3 mm upwards, generally below the displacements provided by the PLAXIS 3D model. The agreement was good in general, considering the difficulty when comparing very small displacements. The differences could be due to the simplifications assumed in the geotechnical model and to the decoupling of the structural and the geotechnical model, an issue considered in a section below. The effect of the tunnel excavation in terms of settlements was almost negligible, and it was not required to inject additional grout. Measured displacements due to the excavation were around 1 to 1.5 mm at the foundation level (downwards). PLAXIS model predicted smaller settlements, around 0.5 mm. The settlements due to the clay consolidation were negligible as well (both, measured and computed).

Figure 7 presents a 3D view of the geometry and the computed displacements due to the excavation of the tunnel in the historic building without compensation grouting. Maximum settlement is 3.4 mm at the oldest area of the building (without basement) and probably the most vulnerable. When the compensation grouting was simulated in the model, maximum displacement occurred in the new area, at the underground parking (4 mm upwards), an area less sensitive to imposed displacements. Finally, the impact of the tunnel on “La Farinera” was negligible. This case is an example of direct interaction between a tunnel and a historic building, but that interaction is less strong than in the previous case, due mainly to the techniques used and to the greater cover of the tunnel.

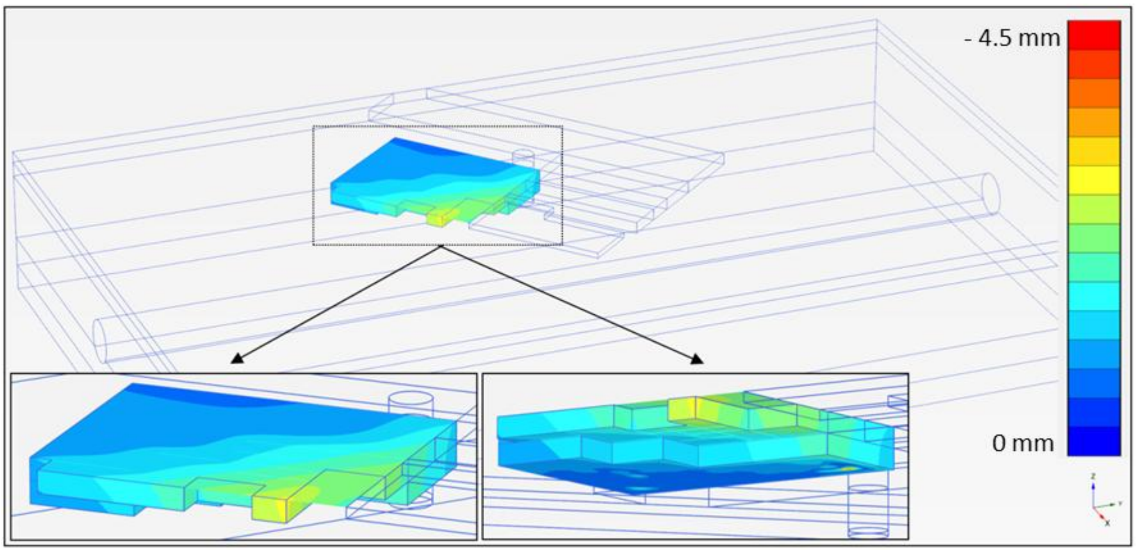

Figure 7. *Movements (downwards) on the foundations of the Farinera building due to the tunnel excavation, without compensation grouting. Maximum settlement is 3.4 mm in the oldest area of the building.*

THE “SAGRADA FAMILIA” BASILICA

This example represents a typical conflict between preservation of world historic heritage and urban development with an impact beyond technical aspects. Indeed, the interaction between the tunnel and the basilica, became a controversial issue and even a topic for political discussions. Some aspects of this interaction and details on the construction have been published already (Katzenbach et al., 2011; Rodríguez-Escribano and Blanco-Zorroza, 2012; Alonso and Ledesma, 2015, 2022; Ledesma and Alonso, 2017). Here, some additional issues particularly related to the numerical analyses of that interaction are described.

The Basilica, a temple still under construction, was initiated in 1882 by architect Antoni Gaudí. In February 2026 the Sagrada Família has culminated the tower of Jesus Christ with the upper arm of the cross. This completes the exterior of the central tower, the Temple’s tallest (172.5 m). In 2005, the original parts of the basilica built by Gaudí were named UNESCO world heritage. A Tunnel Boring Machine, Earth Pressure Balance shield type (TBM-EPB), with 11.5 m in diameter was used for the excavation. In the centre of the city the tunnel followed streets to avoid passing below existing buildings. These streets are only 20 m wide, and the impact of the tunnel on the Temple was a main concern. The project proposed to build a wall of stiff piles (1.5 m in diameter, 41 m in length), to separate the tunnel from the temple, as shown in Figure 8, a solution that has been considered by several authors to protect sensitive constructions from tunnelling (Bilotta, 2008; Bilotta and Russo, 2011; Ledesma and Alonso, 2017; Franza et al., 2021). A capping beam connected all pile caps. Figure 9 shows a view of the basilica during the construction of that pile wall and Figure 10 a typical soil profile in the area of the basilica, where at the tunnel level, tertiary materials predominate, particularly sands and clays below water table. The designed pile wall was not continuous, as there is a groundwater flow in the city, from hills to sea (that is, perpendicular to the wall), and a continuous wall could create an underground dam, preventing that flow. Numerical hydrogeological models concluded that the sandy layers were able to facilitate the flow, thus groundwater levels were expected to change less than 1 m, which is the limit required by the local Environmental Agency (Pujades et al., 2015).

A fundamental issue in this type of interactions is the evaluation of the impact of tunnel on the existing construction. It was assumed, by the technical team involved, that failure of the tunnel was not feasible due to the construction procedure: an EPB shield is a closed face excavation system and a large global sinkhole is not likely. However, a local one is feasible, as the chamber at the front of the EPB has a capacity of about 100 m^3. Therefore, it is important to keep the chamber almost full with a support pressure, to avoid a sudden amount of material entering and generating a sinkhole. That is, the operation of the EPB is crucial to reduce the impact of the excavation on nearby structures. However, being the risk of failure negligible, the question is how much will be the displacement of the towers of the temple, because the risk of generating some cracks due to tunnel induced settlements is not negligible.

The project of the tunnel was developed from 2000 (initial studies) until 2008, when the construction began. The first train crossed the tunnel in 2013. Finally, a set of three additional vertical shafts for emergency exits were finished in 2021. During the design phase, several numerical models were carried out to predict the effect of the pile wall and the expected displacements generated by the excavation of the tunnel considering different values of volume loss, corresponding to different scenarios (i.e., normal operation, malfunctioning of the rear bentonite injection, etc.). Software FLAC 3D was used for that purpose (Itasca Consulting Group, 2005), and the Elastic-Mohr Coulomb constitutive model was considered. It was a common constitutive model used to predict displacements in tunnel excavation problems at that time. Nowadays it is well known that far away from failure, nonlinearity of the soil stiffness at low strains plays an important role when predicting displacements, and therefore, new improved elastoplastic models have been developed in the last 15 years (Benz, 2007; Benz et al., 2009; Clarke, 2009; Clayton, 2011; Castellón and Ledesma, 2022a,b).

In 2008, version 9.01 of Plaxis 2D software incorporated a version of the Benz model called Hardening Soil Model with Small Strains (HSS model) and it was possible to improve the simulations from the project considering that effect. The tunnel was already under construction, but still far from the Sagrada Familia temple, thus there was time for a quick analysis of the tunnel impact using new constitutive models. Therefore, several 2D numerical analyses using HSS model were developed to check the original predictions. This is a good example about how research can be transferred to engineering practice and eventually improve or confirm a previous design.

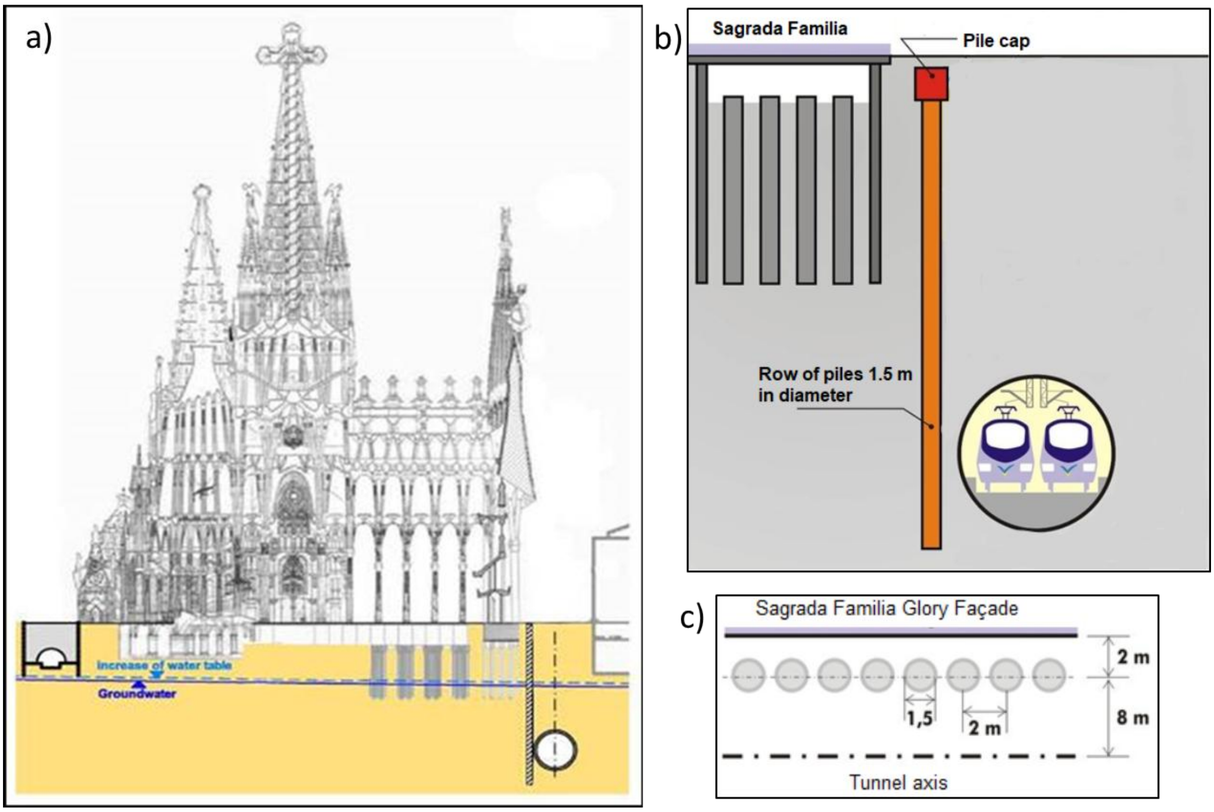

Figure 8. a) *Sketch of the basilica including the pile wall and the tunnel at the right. On the left, there is an old Metro tunnel close to the surface.* ***b)*** *Detail of the pile wall and the tunnel.* ***c)*** *Plan view of the row of piles separating the tunnel and the basilica.*

Figure 9. *Construction of the pile wall along Mallorca street, close to the Sagrada Familia basilica.*

Figure 11 shows the displacements obtained using HSS model and different geometries. Details of the parameters involved are presented in Ledesma and Alonso (2017). The results correspond to a tunnel volume loss of 0.2%, which was an upper bound value of all values measured in the previous monitored sections before reaching the basilica. It is well known that TBM performance needs a “learning curve” (learning phase period) to reach maximum efficiency (El-Kelesh et al., 2026) and volume loss values were decreasing from 0.1% at the beginning to values below 0.05% when approaching the temple. In Figure 11, cases a) and b) correspond to cross sections with the Sagrada Familia on the left and conventional buildings on the right, represented by their weight only. Case a) does not include the protective pile wall whereas in case b) is included as designed in the project. Cases c) and d) represent similar conditions as a) and b), but considering a basement in the buildings in front of the temple and simulating pile foundation for the Sagrada Familia. In fact, the author had some concern about the performance of those buildings, as they were not protected with a pile wall and the tunnel volume loss may affect them directly (i.e., if the gap between excavation and lining is not properly grouted, it may close generating settlements where there is no protection). However, those buildings were modern reinforced concrete buildings, less sensitive to settlements. Note that in Figure 11 all cases show a maximum displacement of about 16 mm at the tunnel crown. Without a protective pile wall, computed settlements at the Glory façade of the Sagrada Familia reach about 11 mm – cases a) and c) -, whereas with that wall, settlements reach 5 to 6 mm.

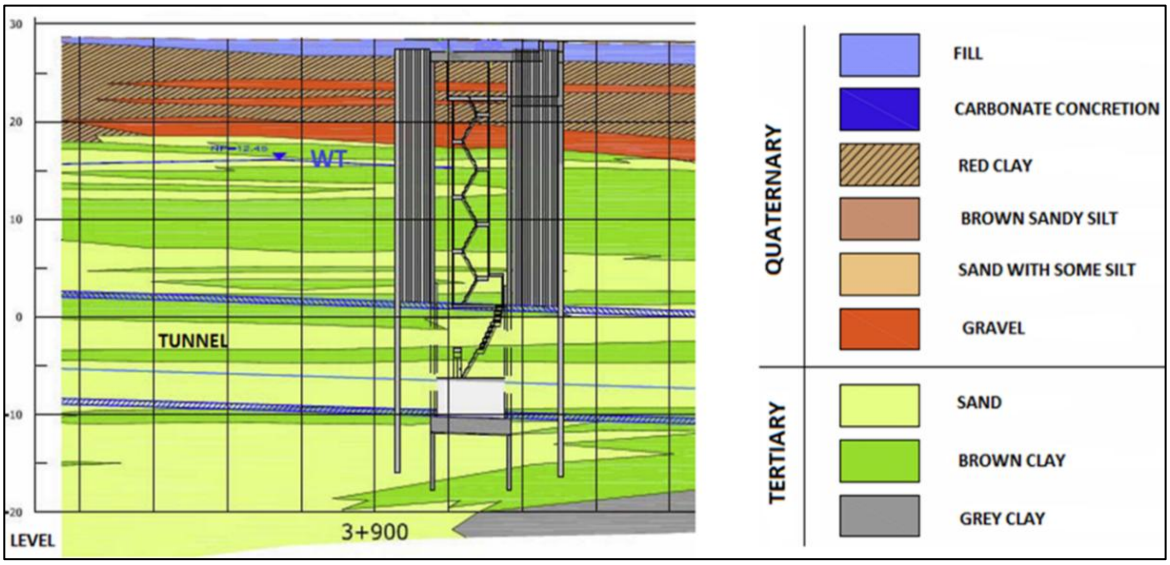

Figure 10. *Soil profile at the Padilla vertical shaft, close to the Sagrada Familia basilica.*

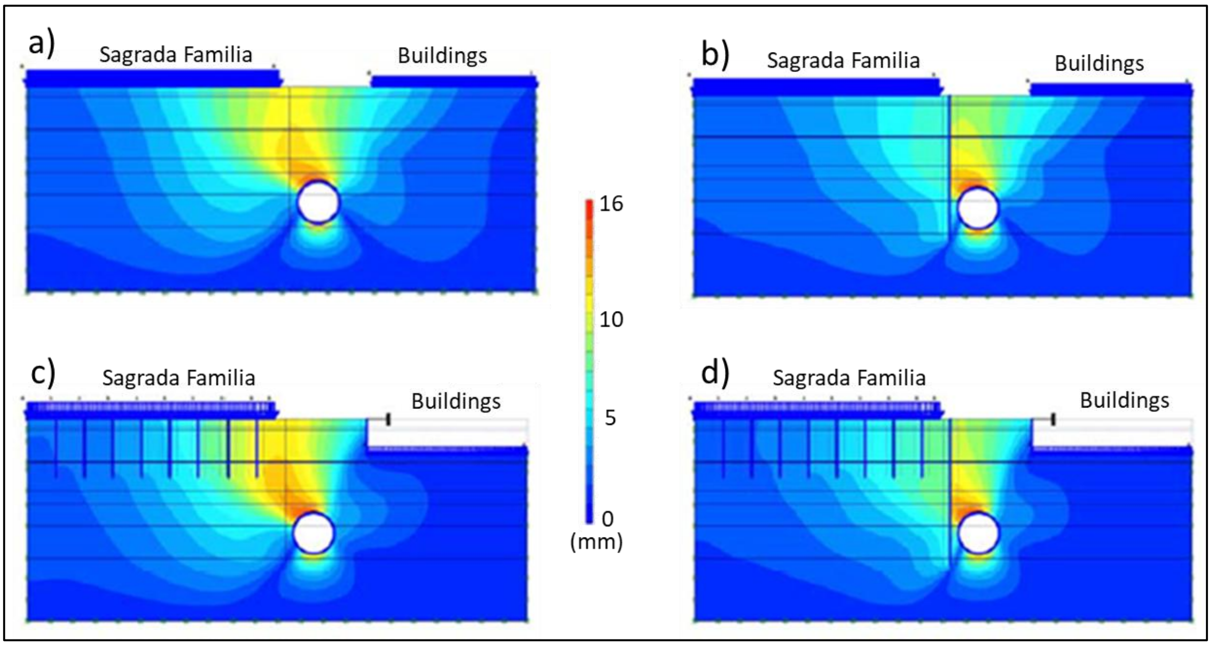

Figure 11. *Soil displacements in mm computed using Plaxis 2D and the HSS model for a tunnel volume loss of 0.2%.* ***a)*** *Case without wall, Sagrada Familia without piles and buildings without basement.* ***b)*** *Case with wall, Sagrada Familia without piles and buildings without basement.* ***c)*** *Case without wall, Sagrada Familia with piles and buildings with basement.* ***d)*** *Case with wall, Sagrada Familia with piles and buildings with basement.*

Regarding the buildings in front of the temple, settlements are below 5 mm in all cases, a very small value. Note that in the case of a building with basement, the settlements are very small indeed, despite being building foundations very close to the tunnel. This effect can be explained by the fact that soil stiffness in that constitutive model depends on the stress history and the clay in that area is slightly overconsolidated due to the excavation of the basement. That value of 5 to 6 mm of settlement of the Glory façade was an expected value for a worst-case scenario of volume loss. It was difficult to analyse the effect of such settlement on the structure of the temple, but using simplified procedures based on the combination of horizontal strain at the base of the temple and the angular distortion of adjacent foundations, a negligible damage was predicted (Boscardin and Cording, 1989). The prediction of damage based on simplified charts is a common procedure, although may not be appropriate for historic buildings with complex geometry.

When dealing with small displacements, thermal movements may be difficult to distinguish from tunnel induced movements. Note that due to a thermal difference of 10ºC between day and night, the expected displacement of a tower of 100 m high is about 10 mm. Therefore, an important effort was devoted to define the reference points of the monitoring system and to analyse the recorded displacements to separate thermal effects.

An additional risk to consider was the verticality of the pile wall. The EPB machine cannot excavate reinforced concrete structures and the pile wall should not intercept its path. Due to the proximity of the pile wall to the temple foundations and to the boundary of the tunnel, it was very important to check the verticality of the piles before pouring the concrete.

Finally, the tunnel was successfully excavated next to the Basilica inducing displacements of about 1 to 2 mm, which corresponded to a volume loss of about 0.1% (Alonso and Ledesma, 2022). Part of the success was due to the tight control of the EPB shield, with an independent external team replicating and checking the operations of the driving team inside the boring machine.

LESSONS LEARNED AND FUTURE CHALLENGES

The examples described here cover a wide type of interactions between historic constructions and the excavation of a tunnel. Although it is difficult to classify historic buildings (Al-Sakkaf et al, 2020) a classical approach considers 3 grades: monumental construction (as the Sagrada Familia basilica), building of regional importance (as the "Farinera" building) and classified local building (as the "Torre del Fang"). Each grade allows for a different impact in case of conflict with a new construction and those criteria were considered in the examples above. However, it is a controversial issue to what extent we can modify a historic construction, including its foundations, surroundings, etc. (Tsatsanifos, 2005).

From the predictive point of view, nowadays there are mature procedures to analyse the impact of a tunnel on a historic building. However, there are challenges that require additional future research. In particular, coupling the structural and the geotechnical analysis is still far from being a routine (Pascariello et al., 2023; Hemeda, 2024). Regarding soil models, elastoplastic constitutive laws, including high stiffness at small strains seem to be appropriate in many situations which are away from failure conditions. Regarding structural models, consideration of the masonry blocks and joints with mortar is possible, either as individual components or globally as a composite material (Lourenço and Gaetani, 2022), but the computational cost increases significantly if a coupled approach is intended. In addition to that, defining the geometry of the foundation and obtaining structural stiffness parameters become a difficult task, and non-destructive testing techniques are gaining increasing attention (Diz-Mellado et al., 2021). The goal of the predictive task is to assess the risk of potential damage to the historic construction, quite often carried out using simplified charts developed for standard buildings (i.e., Boscardin and Cording, 1989). Future research may improve those simplified assessment procedures.

From the construction point of view, the excavation of tunnels by means of a TBM has increased significantly the safety of this type of projects in terms of workers safety and impact on ground displacements. Volume loss is nowadays well below 1% in most situations (Mair, 2008), and below 0.1% in the examples described. The risk of a face collapse in the tunnel is reduced to a limited volume in the chamber, controlled by the EPB drivers. To reduce the potential risk of a mistake from the driving team, an independent external team was continuously checking the operations and decisions from the drivers in the tunnels described above. This is not a routine procedure, but it is advised when historic buildings may be affected. Regarding vertical shafts, its diaphragm walls were preferably excavated by hydromills rather than hydraulic grabs, at least in La Farinera area and close to the Sagrada Familia Temple.

Monitoring was also a fundamental task; an independent company, reporting to the managing team, carried it out in a continuous manner. However, the interpretation of measurements was not straightforward, basically because of the huge amount of data to be analysed. Probably, in the near future, the routine use of BIM technologies adapted to this type of works will enhance the planning and control of the construction, hence reducing the associated risks (Providakis et al., 2019).

CONCLUSIONS

The paper presents three examples of historic constructions affected by the excavation of a tunnel and how the expected impact was managed and reduced. Each case corresponds to a different protection grade: a local classified building, a building of regional interest and a world heritage construction. The solution adopted was different for each case as well. Despite the technical challenges, the impact of the tunnel on the constructions was negligible. Managing uncertainty is a typical issue in Geotechnical Engineering, but when dealing with historical constructions, the lack of information combined with the risk involved results in a challenging work. Past experiences always provide a source of lessons learned and potential difficulties that can be useful for future cases; therefore, this paper aims to contribute to their dissemination.

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