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Integrating MT-InSAR and conventional monitoring with numerical analysis for tunnel excavations: A case study

Intégration de la surveillance MT-InSAR et conventionnelle avec l'analyse numérique pour l'excavation des tunnels: Un cas d'étude

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ABSTRACT: Multi Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) is a remote sensing technique used for monitoring surface deformations with high precision and spatial resolution. This study aims to evaluate the effectiveness of this technique for tunnelling monitoring by complementing data gathered by conventional optical monitoring and comparing the resulting dataset with FE numerical analysis using Plaxis3D software. The comparison generally reveals good agreement, indicating the potential of MT-InSAR for monitoring tunnelling-induced displacements. The integration of MT-InSAR with conventional monitoring and numerical analysis can provide a comprehensive understanding of the behaviour of the ground during the excavation process, contributing to the development of efficient and safe tunnelling practices.

RÉSUMÉ: Le radar interférométrique à synthèse d'ouverture multitemporelle (MT-InSAR) est une technique de télédétection utilisée pour surveiller les déformations de surface avec une précision et une résolution spatiale élevées. Cette étude vise à évaluer l'efficacité de cette technique pour la surveillance du creusement des tunnels en complétant les données recueillies par le contrôle optique conventionnel et en comparant l'ensemble des données obtenues avec l'analyse numérique par éléments finis à l'aide du logiciel Plaxis3D. La comparaison révèle généralement une bonne concordance, ce qui indique le potentiel de la technique MT-InSAR pour la surveillance des déplacements induits par le creusement de tunnels. L'intégration de MT-InSAR à la surveillance conventionnelle et à l'analyse numérique peut fournir une compréhension complète du comportement du sol pendant le processus d'excavation, contribuant ainsi au développement de pratiques de creusement de tunnels efficaces et sûres.

Keywords: Tunnelling; MT-InSAR; finite element; displacements; monitoring.

1 INTRODUCTION

The excavation of large diameter tunnels in urban areas may represent a potential risk for existing buildings, particularly in complex geological conditions and in densely exploited underground space. Monitoring tunnelling induced displacement during construction is therefore required to ensure the structural health of the above buildings and nearby infrastructures and to guarantee their serviceability levels. Datasets gathered from monitoring can be used to validate the numerical analysis of complex soil-structure interactions during tunnelling, thus enabling a better support to corrective measures during construction.

Nowadays, in addition to conventional optical prisms and levelling devices, buildings' movements can be monitored by processing data from synthetic aperture radar (SAR) satellites. The ability of radar satellites to measure the field of displacements induced by tunnel excavations in urban areas has quickly improved in the last decade (Perissin et al., 2012; Barla et al. 2016; Milillo et al, 2018; Giardina et al., 2018). High-resolution SAR satellites, such as the COSMO-SkyMed (CSK) or TerraSAR-X constellations, have been launched and new and more advanced ones are going to be. At the same time, data processing techniques have been implemented in research and commercial platforms and the use of Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) technique for structural health monitoring of buildings and infrastructures has emerged (Ferretti et al., 2011; Caprino et al., 2023).

In this paper, ground and buildings movements measured by MT- InSAR analyses of satellite images recorded during tunnel construction for a branch of metro Line 9 (now Line 10 south) in the city of

Barcelona (Spain) are used to complement data gathered by conventional optical monitoring and compared with the results of Finite Element analysis of the effects of tunnelling on a residential building in the area. This allows to discuss the potential and limitations of MT-InSAR to provide additional information for the verification and validation of numerical models in urban tunnel construction.

2 CASE STUDY

2.1 Ground conditions and works

The paper refers to the case study of a mechanised tunnel excavation in the city of Barcelona. The excavation, belonging to the Line 9 (L9) project, was executed with a 12.06 m diameter Earth Pressure Balance (EPB) Tunnel Boring machine (TBM) and was part of the L9 branch connecting Barcelona to its port logistics activities zone. Tunnelling, in this area, started from Foneria station and was headed towards Ildefons Cerdà station (from the left to the right in Figure 1), about 700 m apart from the first one. The tunnel alignment crosses a densely urbanised area with a cover to diameter ratio, C/D, in the range 2.5-3.0. The geological profile along the alignment (Figure 1) involved Quaternary soft alluvial and detrital deposits (QM, QS and QR), overlaying Miocene hard formations (M1U and M2L) consisting of siltstone and argillite. The water table is located in the alluvial deposits at a depth of about 8 m from the ground surface and at 22-28 m above the tunnel crown.

The first 100 m or so of the excavation were quite challenging due to the presence of mixed ground conditions at the tunnel face, including a thin layer of highly permeable gravels at the tunnel crown. This contingency caused loss of pressure in the EPB cutter head and, as a result, some overexcavation was experimented just before the boring machine approached a well monitored 10-storey residential framed building (Figure 1) having a 2-level underground parking garage. Below the building, tunnelling became even more difficult because the alignment curves (radius of curvature of 300 m) right where the building south façade is located (Figure 1). The challenging tunnelling conditions led to volume losses in the range 0.5-1.0% that gave rise to significant ground movements. As the EPB machine moved towards the north façade of the building (from Block B towards Block A in Figure 2b), the mixed ground conditions at the tunnel face gradually changed to approximately uniform conditions with the harder Miocene materials occupying nearly the whole excavation section. Also, the tunnel depth slowly increased contributing to lower observed volume losses.

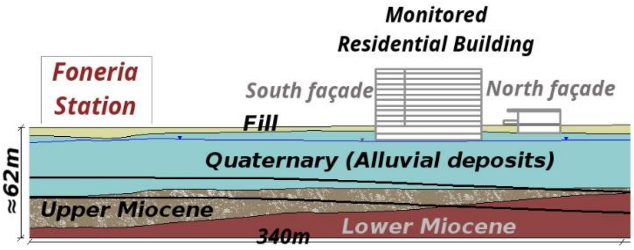
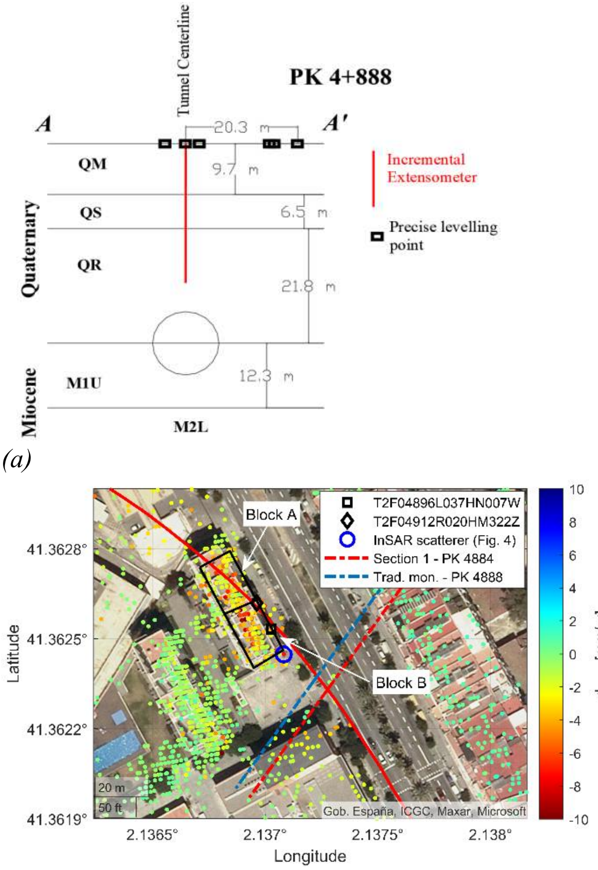


Figure 1. Geological profile in the area of study.

2.2 Monitoring

A comprehensive instrumentation system was set up to monitor tunnelling operations. Manual and automatic instruments were used to measure surface and subsurface ground movements (Figure 2a), as well as 3D movements of the framed building and its basement (Di Mariano et al., 2021).



(a)

(b)

Figure 2. (a) Conventional monitoring at PK4888; (b) InSAR scatterers, selected monitoring sections and LPs.

To complement the database of measurements taken with conventional monitoring, for the purpose of this work MT-InSAR data were also used (Figure 2b). 32 SAR images were acquired by the TerraSAR-X full archive in Stripmap mode in an ascending path direction, from January 7th 2009 to October 2nd 2012, and processed by TRE-Altamira by SqueeSAR®, an advanced algorithm for surface displacement detection developed by Ferretti et al. (2011). Further details on the methodology can be found in Di Mariano et al. (2024).

3 NUMERICAL MODELLING

To study the complex Soil Structure Interaction (SSI) phenomenon produced by tunnelling below the monitored residential building, fully coupled 3D numerical analyses were carried out with the commercial Finite Element (FE) code PLAXIS 3D. For simplicity purposes, a geological profile with horizontal stratigraphic layers was considered (Figure 3). The numerical model reproduces the tunnel curved alignment, the operating parameters of the EPB boring machine and the installation of the lining. It also reproduces the conicity of the shield, the weight of the back-up trailer and the eccentric position of the lining with respect to the EPB shield. The model replicates the excavation process with a step-by-step procedure that allows to consider the segments width. Nevertheless, the segmentation of the lining in the tunnel transverse direction is not considered.

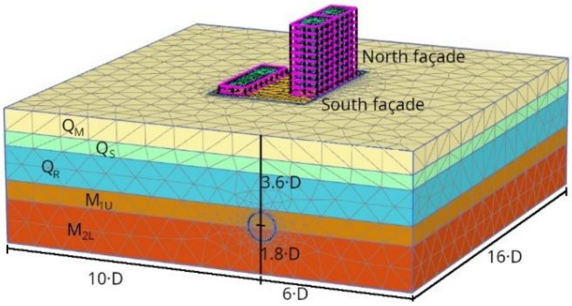


Figure 3. FE model (D = tunnel diameter).

A non-linear type of the hyperbolic constitutive model, formulated in the frame of friction hardening plasticity, was used to represent the behaviour of all ground materials. The model considers the nonlinear ground stiffness decay as shear strains increase. On the other hand, linear-elastic laws were assumed for all structural elements, which were far from failure conditions.

Table 1. Soil parameters.

	(kN/m^3)	c' (kPa)	'	$E_{50,ref}$ (MPa)	$E_{ur,ref}$ (MPa)	$E_{oed,ref}$ (MPa)	m	K (m/s)
Q_M	17	0	29	16	48	12	0.9	5e-4
Q_S	19.6	0	34	11	33	10	0.65	4e-4
Q_R	21	1	30	15	46	10	0.6	1e-5
M_{1U}	21	1	36	46	180	25	0.8	2e-5
M_{2L}	22.5	10	33	278	833	100	0.9	1e-7

The main geomechanical parameters used in the analysis reported in this paper are shown in Table 1. They were inferred from both laboratory and in situ investigations. A few attempts have been made to adjust the initial estimate of soil stiffness parameters to adequately reproduce the ground movements observed along the line, also considering the effect of contingency ground treatments that were undertaken during the underpassing of the residential building in the model.

4 RESULTS

Figure 4 shows a comparison between the settlement time history evaluated by processing SAR images of the scatterer, circled in blue in Figure 2, and the corresponding settlement calculated by FEA. In the same figure the settlement profile of the close LP T2F4896L037HN007W has also been added for further comparison. Overall, the numerical results match well both InSAR and optical levelling data.

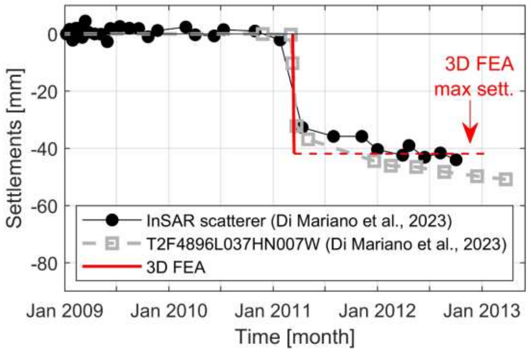


Figure 4. Time series comparison between InSAR scatterer, levelling point and corresponding FEA output.

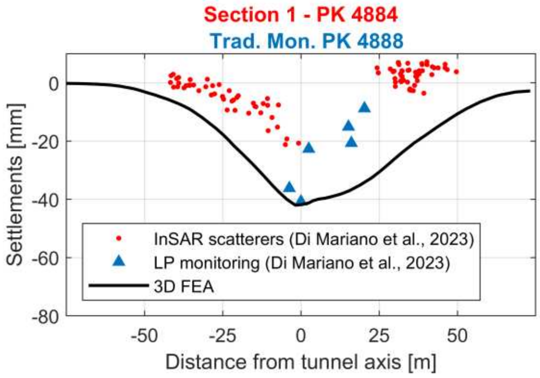


Figure 5. Settlement trough: satellite data (InSAR), conventional optical levelling (LP) and FEA results.

In Figure 5 the displacement of Permanent Scatterers and Levelling Points after the full passage of the TBM across the transverse section at PK4888 are compared with the computed settlement profile. The PS displacements along the satellite LoS, gathered in a 10 m wide band across the section, were projected along the vertical direction, assuming that the ground displacements due to tunnelling were predominantly vertical. This assumption may lead to an acceptable error, lower than 5% on the maximum settlement (Della Ragione et al., 2023). The levelling points (same Figure 5) also confirm that such error is not large.

The FE calculated profile matches only two LP measurements, while it generally overestimates the overall settlement trough that, despite the scatter of the MT-InSAR data, emerges clearly from both sets of measurements. Further inspection is needed to understand such discrepancy and validate the model.

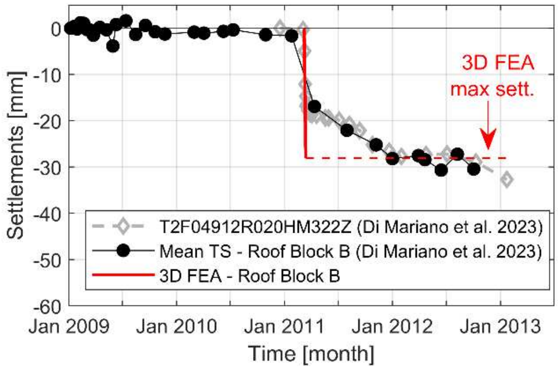


Figure 6. Block B roof displacement (InSAR, LP, FEA).

Finally, in Figure 6 the time histories of displacement of the PSs that belong to the roof of Block B is averaged and compared both with that of the prism T2F04912R020HM322Z, on the same building roof, and with the corresponding numerical calculation. A good matching can be appreciated in this case.

5 CONCLUSIONS

The paper compares the movement monitored by processing SAR images collected by the satellite TSX1 (TerraSAR-X) during the construction of Line 9 of Barcelona metro with the numerical results of the construction process obtained with the commercial code Plaxis3D. Data gathered during construction by conventional optical monitoring are also shown. The comparison indicates the potential of MT-InSAR to monitor the effects of tunnel excavation in urban areas. Even though MT-InSAR cannot substitute terrestrial measurements, since the latter provides a reliable benchmark for the former, it can indeed complement optical monitoring as a mean to verify and validate numerical modelling. This is possible due to the large amount of data than can be retrieved by processing images even long after the work completion.

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