Settlements Induced by the Metrobus Tunnel Excavation in the Historic Town of Brescia (Italy)

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1. Introduction

This paper presents the study carried out to predict ground movement induced by the construction of the tunnel for the first underground metropolitan line in the city of Brescia, Italy, the "Metrobus Brescia" project. The project comprises the construction of a 13 km light-railway line which includes a 5.9 km single tunnel. The tunnel was excavated between 2005 and 2009 with a Tunnel Boring Machine equipped with a shield and earth pressure balance technology (EPB-S). The machine is suitable for most soils, can operate below water table and is capable of automatically laying the permanent tunnel lining. The shield diameter is 9.15 m and the permanent lining diameter is 8.85 m, consisting of pre-cast reinforced concrete elements of 0.35 m thickness. The excavation was carried out mainly in alluvial gravelly soil deposits and the soil cover is generally in the range of 17-20 m. The tunnel layout lies beneath the center of Brescia where a number of buildings of historical and social interest are located (Figure 1).

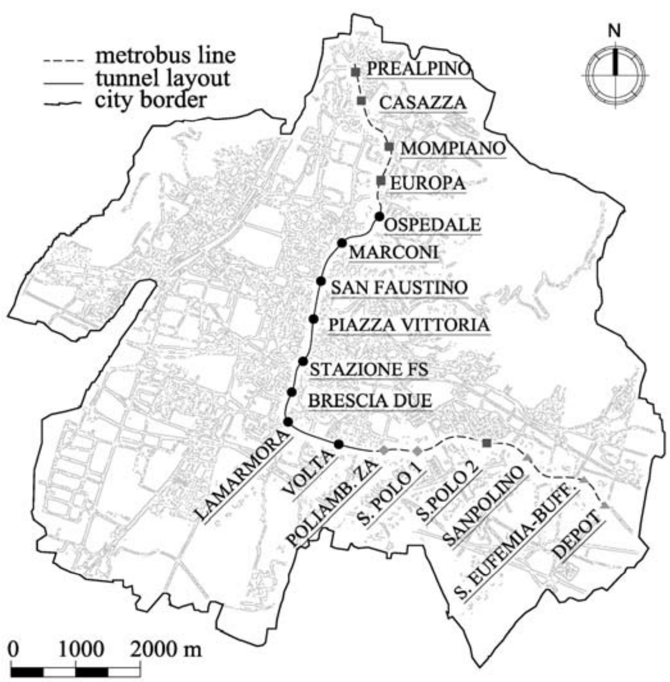

Figure 1 – Layout of the Brescia Metrobus light-railway line

Among the most important structures, Palazzo della Loggia has been the venue of the city administration since its construction between the 15th and 16th centuries, under the Republic of Venice domination.

Before the authors' involvement the ground movement induced by the Metrobus tunnel was computed using the classic empirical equation proposed by Peck in 1969; such an approach has been recently used with acceptable results to estimate settlements induced by the excavation of Line-1 extension in Milan [1]. In this study the effect of tunneling was analyzed using a plain-strain finite element model. To predict soil movement and building response, a number of numerical simulations were carried out on a calibration-purpose model and preliminary results were compared with measured settlements obtained from a number of tunnel sections previously constructed. The model was subsequently used to predict vertical settlements induced at Palazzo della Loggia section [2].

2. Soil Profile and Parameters

2.1 Site Characterization

The tunnel excavation was carried out mainly in alluvial gravelly soil deposits (Figure 2). Soil characterization was performed before the authors' involvement and included a comprehensive preliminary desk study with results of pre-existing soil explorations, and a site investigation. The latter activity consisted of 22 borings with execution of Standard Penetration Tests, geophysical down-hole tests (retrieved soil samples were mainly disturbed and could allow only for classification tests).
Figure 3a shows a schematic soil profile along the layout of the tunnel near Palazzo della Loggia. From the ground surface (146.3 m a.s.l.) the following layers are encountered:

- Made ground: mainly cohesionless, medium to loose soil, N_{SPT}=15-25. Thickness varies between 1 m and 6 m along the line and is approximately 5 m at Palazzo della Loggia section.
- Gravel: well graded (45-60% gravel, 20-35% sand, 10-25% silt and clay) medium to dense soil, N_{SPT}=35-60. Sandy and clayey lenses as well as weak cemented volumes are encountered along the tunnel layout.
- Weathered and fractured limestone: this geological unit was encountered only at Palazzo della Loggia section at an elevation below 118-119 m a.s.l. (z=27-28 m).

The water table is a few meters below the tunnel axis in the north part of the city and rises above the tunnel axis southward, at Palazzo della Loggia it is located at an elevation of 118 m a.s.l. (Figure 3b).

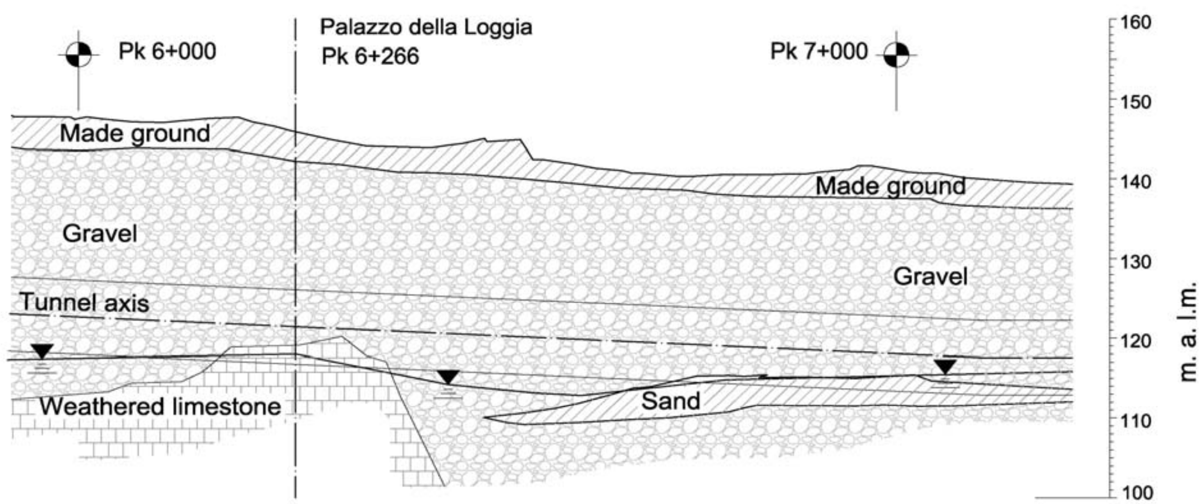

Figure 2 – Schematic soil profile along tunnel layout and around Palazzo della Loggia (km 6+266)

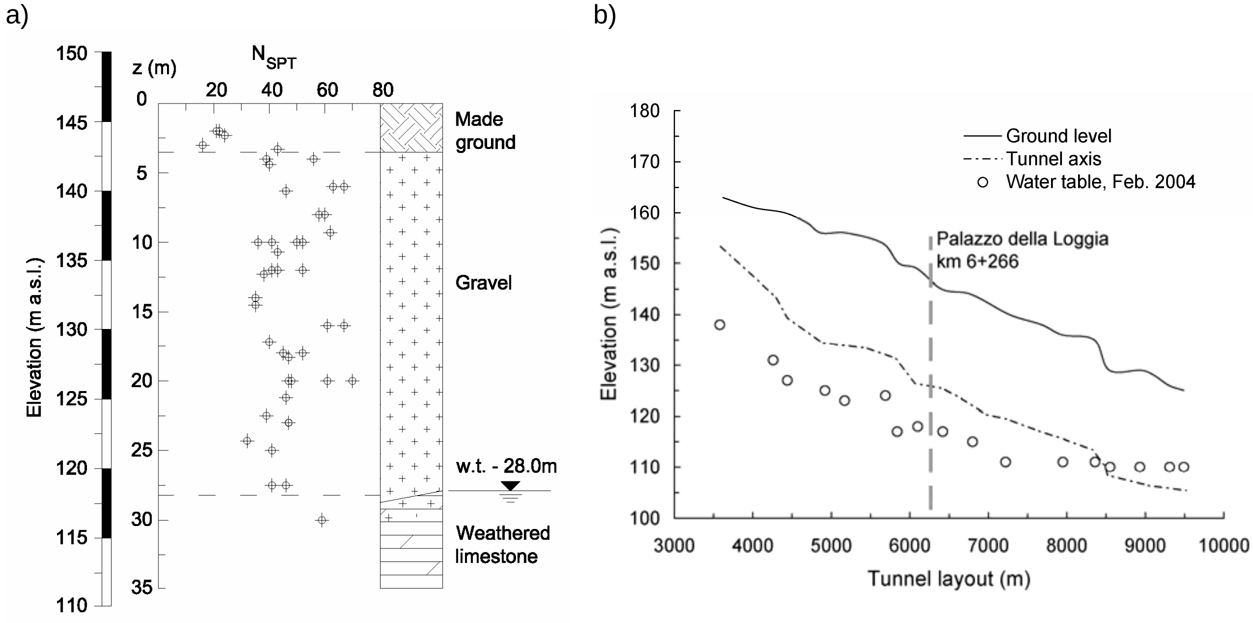

Figure 3 – Soil profile near Palazzo della Loggia, km 6+266 (a), and water table profile (b)

2.2 Constitutive Model and Soil Parameters

The ground movement induced by the tunnel excavation was studied through a number of finite element analyses using the code Plaxis (version 8.6, Delft University) with a plain-strain, 15-node triangular element model.

The mechanical behavior of the soil around the excavation was described using the constitutive model Hardening Soil, available in the code library [3]. This is an elastic-plastic rate independent model with isotropic hardening and stress-dependent stiffness according to a power law.

The shear resistance parameters were determined based on the authors' experience with local soil deposits and with empirical correlations with results from SPT tests [4, 5, 6].

The soil stiffness was estimated from experimental data obtained from geophysical down-hole tests performed along the tunnel axis, as described by Rampello and Callisto (2003) [7].

In the Hardening Soil (H-S) constitutive model the elastic behavior of granular soils is defined by isotropic elasticity through a stress-dependent Young's modulus:

$$E' = E'^{ref}\left(\frac{\sigma'_3}{p^{ref}}\right)^m$$

where σ'_3 is the minimum principal effective stress, $p^{ref} = 100kPa$ is a reference pressure, E'^{ref} and m are model parameters. The Young's modulus E'^{ref} has been related to the shear modulus at small strain G_0 obtained from down-hole tests, and the model parameter E'^{ref}_{50}, which identifies the secant stiffness modulus at the reference confining pressure p^{ref}, was estimated adopting the Poisson's ratio $\nu = 0.20\text{-}0.25$ and assuming $E'^{ref}/E'^{ref}_{50} = 10\text{-}12$ in relation to the expected soil shear strains.

The mechanical behavior of the superficial layer of made ground and of the weathered limestone were described using a perfectly plastic model with Mohr-Coulomb failure criterion (M-C) and a liner elastic model (L-E) respectively. Table 1 reports soil constitutive models and parameters adopted in the analyses.

Soil type	Soil model	φ' , °	E'^{ref} , MPa	m	$E_{50}'^{ref}$, MPa
Made ground	M-C	32	-	-	25
Gravel	H-S	36	750	0.4	65
Weathered limestone	L-E	-	-	-	270

Table 1 - Soil constitutive models and parameters

3. EXACAVATION ANALYSIS

3.1 Evaluation of Ground Loss

Before the magnitude of ground movements can be predicted it is necessary to estimate the expected ground loss V_s /V_{exc}. This estimate is generally based on case history data and should include an engineering appraisal that takes into account the adopted tunneling method and site conditions [8]. Alternatively, soil movements can be estimated through the determination of the so called gap parameter [9], which takes into account the ground loss as a function of soil strength and deformation behavior, physical clearance between the excavated diameter and the lining, and workmanship. In the numerical simulations (performed with a plain-strain model), the effect of ground loss during excavation and construction was simulated by applying a contraction to the tunnel lining equal to the ratio V_s /V_{exc}. The numerical value of the applied contraction was estimated with measurement of surface settlements obtained from a number of sections already constructed in soil deposits with geotechnical features similar to those encountered nearby Palazzo della Loggia. Figure 4 shows one of the sections (named SCBF 8 and located at km 7+597) with indication of the soil profile, depth of the water table and tunnel location, while Figure 5a reports vertical settlements taken during tunnel excavation and construction. The most appropriate value of lining contraction was calculated integrating settlement profiles such as the one reported in Figure 5a and dividing the obtained value by the area of the TBM face. Figure 5b shows the variation of surface vertical settlement along the longitudinal tunnel crown axis with the TBM advance: the vertical settlement is normalized by the maximum measured value and the machine advance is expressed both in meters and shield diameters. The reported data show that vertical displacement ahead of the TBM face amounts to 20-22% of the total and starts showing approximately at a distance equal to 2 diameters; ground loss over the shield consists of some other 25-28% of the total and finally, although backfill grouting of tunnel lining is systematically executed, the settlement registered over the permanent lining is approximately 50% of the total.

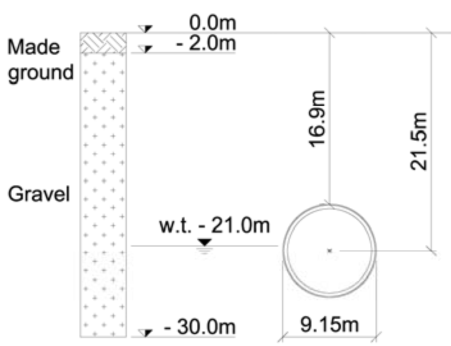

Figure 4 - Calibration section SCBF 8 at km 7+597

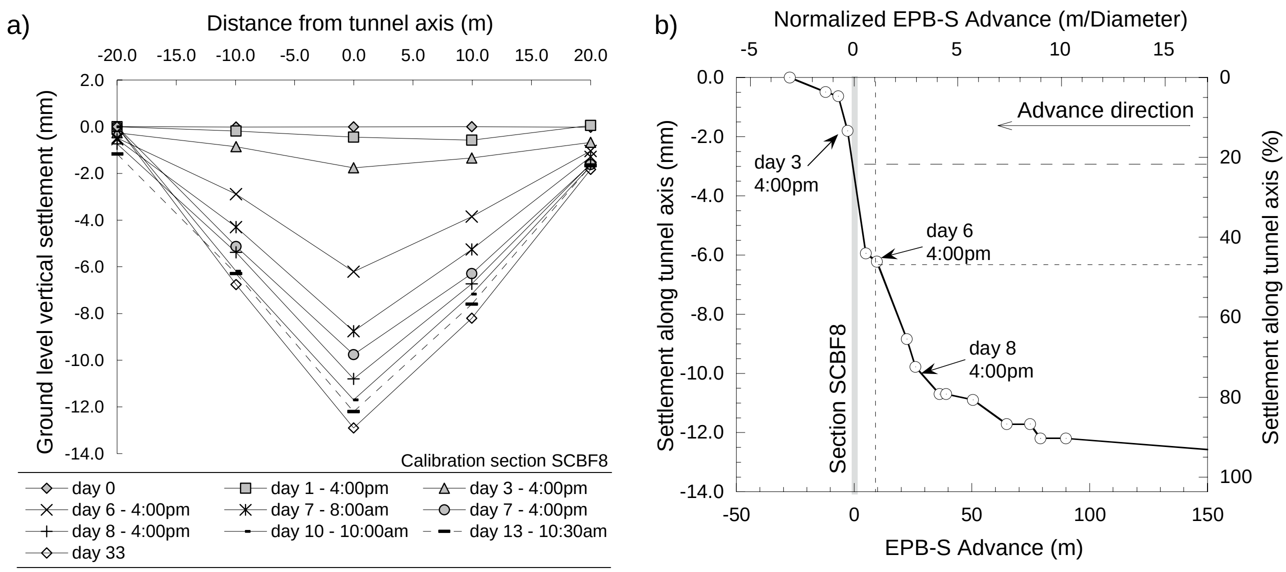

Figure 5 – Measured transverse settlements (a) and variation of surface vertical settlement along the longitudinal tunnel axis with TBM advance (b), calibration section SCBF8

At the time of the authors' involvement an estimated ground loss 0.45-0.50% represented the most likely value with frequency of occurrence in the range of 86-90%.

3.2 Back Analysis and Palazzo della Loggia Settlement Predictions

The back analysis simulations of tunneling through the reference sections were performed assuming the soil profile illustrated in Figure 4 and absence of buildings at the ground surface. Since the examined sections were symmetric, only one half of the tunnel section was taken into account. The soil behavior was described with constitutive models and parameters reported in Table 1 and a lining contraction equal to V_s/V_{exc} was applied instantly during one calculation phase. The effect of a higher contraction as a direct consequence of technical problems encountered during excavation was examined.

Figure 6a shows the main East façade of Palazzo della Loggia, Figure 6b reports a schematic section showing the position of the tunnel and Figure 6c illustrates the tunnel layout and relevant control benchmarks installed around the building area. The two storey building is 30 m high and has a ground plan of 47 m x 30 m. The structure is made of bricks and stones in elevation, covered by wooden floors and cross vaults, and the dome is shaped like a trough vault covered with lead sheets [10, 11]. The foundations are continuous in the West part and are isolated piers in the East part, the foundation level is approximately 5.0 m below ground surface. As documented by Giuriani (2007) [11], the building suffers foundation problems due to partial degradation of the short wooden piles driven for soil improvement purposes in the 15th century. The tunnel axis is located between 23 m and 25 m from the West side of the building and 24.5 m from ground surface. A number of other buildings of different sizes, mainly devoted to residential purposes are located near the palace.

The progressive deterioration of the building foundations and the forthcoming tunnel construction required the consolidation and improvement of the soil beneath the foundations and assessment of building settlements induced by the excavation; the improvement of the building foundation was accomplished only one month before the tunnel excavation, by means of low-pressure grout injection of the cavities left by the degraded wooden piles (preparatory studies are described in [11] Giuriani 2007).

The prediction analysis at Palazzo della Loggia section considered the soil profile represented in Figure 3 and soil constitutive models and parameters reported in Table 1. The presence of the palace and other buildings were conservatively taken into account by applying distributed loads at the foundation levels

(150 kPa for Palazzo della Loggia and 50 kPa for the other buildings), therefore neglecting the stiffness of the structures in elevation.

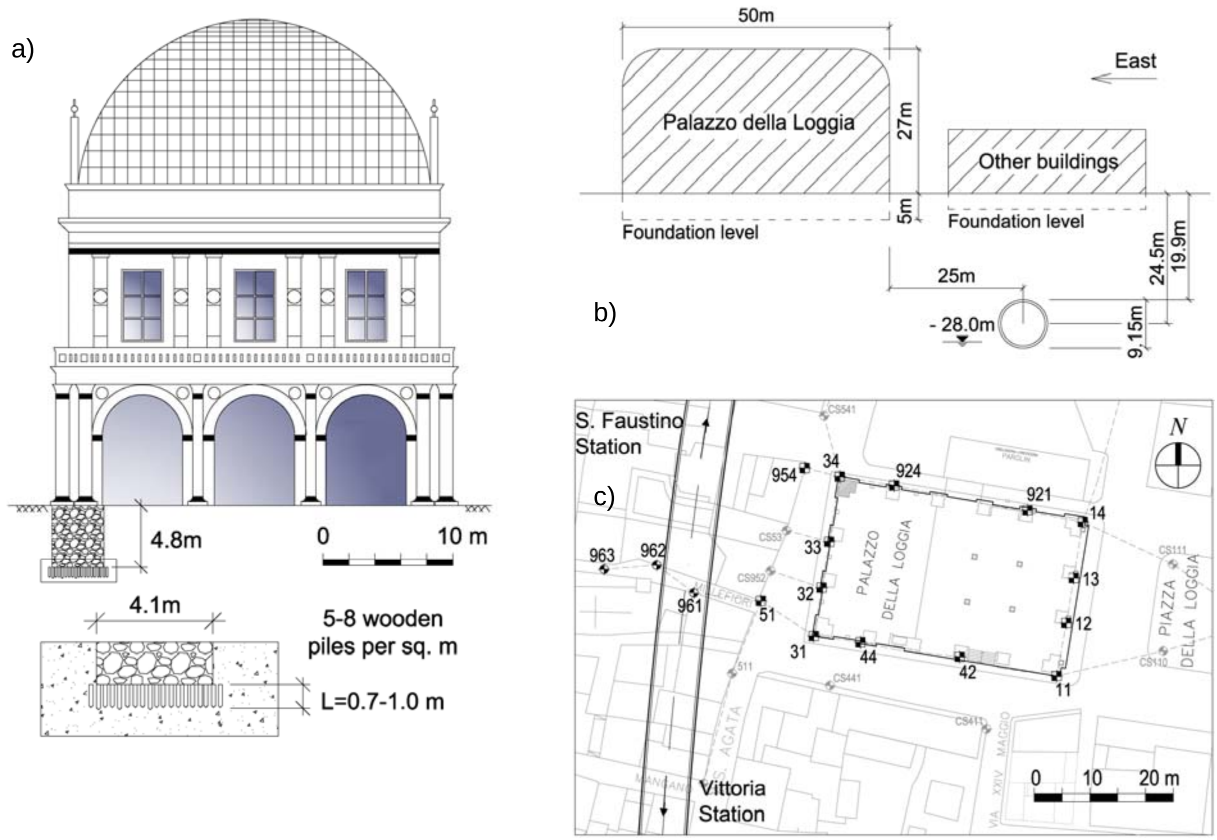

Figure 6 – Palazzo della Loggia East façade (a), schematic cross section (b), building plan view and control system (c)

4. COMPARISON OF OBSERVED AND COMPUTED BEHAVIOR AND CONCLUSIONS

In Figure 7a the vertical displacements measured at ground level 33 days after the excavation and construction of section SCBF 8 are compared with those computed in the numerical analysis and with those estimated with the empirical equation proposed by Peck in 1969 assuming parameter $K=0.35$, according to the settlement estimation in the Metrobus project. Measurements and computations show a satisfactory agreement, particularly regarding the amount of settlement above the tunnel axis (with maximum settlement not exceeding 13-14 mm). However, the amplitude of the ground surface affected by the excavation is significantly underestimated by Peck's empirical correlation, due to the numerical value assumed for parameter K, which affects the transverse distance of the point of inflection from the tunnel longitudinal axis, whereas the FEM computed settlement distribution reproduced the real settlement basin well. The comparison also demonstrates that the value of applied lining contraction, estimated as the ratio between measured settlement and the area of the TBM face, V_s/V_{exc}, is suitable for describing the effects of excavation and construction process on ground movement around the tunnel, although the plain-strain numerical model does not allow appreciating three dimensional and time effects.
To investigate the effects of ground loss, a number of numerical analyses were performed applying values of lining contraction between 0.3% and 1.5%, in order to quantify the effects of technical difficulties during tunneling such as a sudden stop, sudden loss of face pressure, uncontrolled machine tilting and

overcutting, or interruption of backfill grouting of tunnel lining. The expected vertical settlement above the tunnel axis greatly increases with applied contraction values higher than 0.7%. Similarly, the amplitude of the basin increases as a result of the increase in volume of the soil subjected to high shear strains near the tunnel lining (Figure 7b).

Figure 7c shows the results obtained from the prediction analysis at Palazzo della Loggia in comparison with selected measurements of vertical settlements obtained from the control system in Figure 6c. The computed settlement is taken from a horizontal section located at the building foundation level in the numerical model. The maximum vertical settlement, measured along the West side of the building at points 34 and 31, is less than 2 mm, and decreases to values comparable with the control system error within 10 m from the West side of the building (benchmarks 44 and 924), the resulting angular distortion is estimated as 1/5000. The settlement prediction compared well with measurements and confirmed that, due to the distance of the building from the longitudinal axis of the tunnel, the risk of damage was limited. The vertical settlements measured above the tunnel show the effect of the buildings stiffness with reduced settlements and distortions in the sagging zone of the settlement profile.

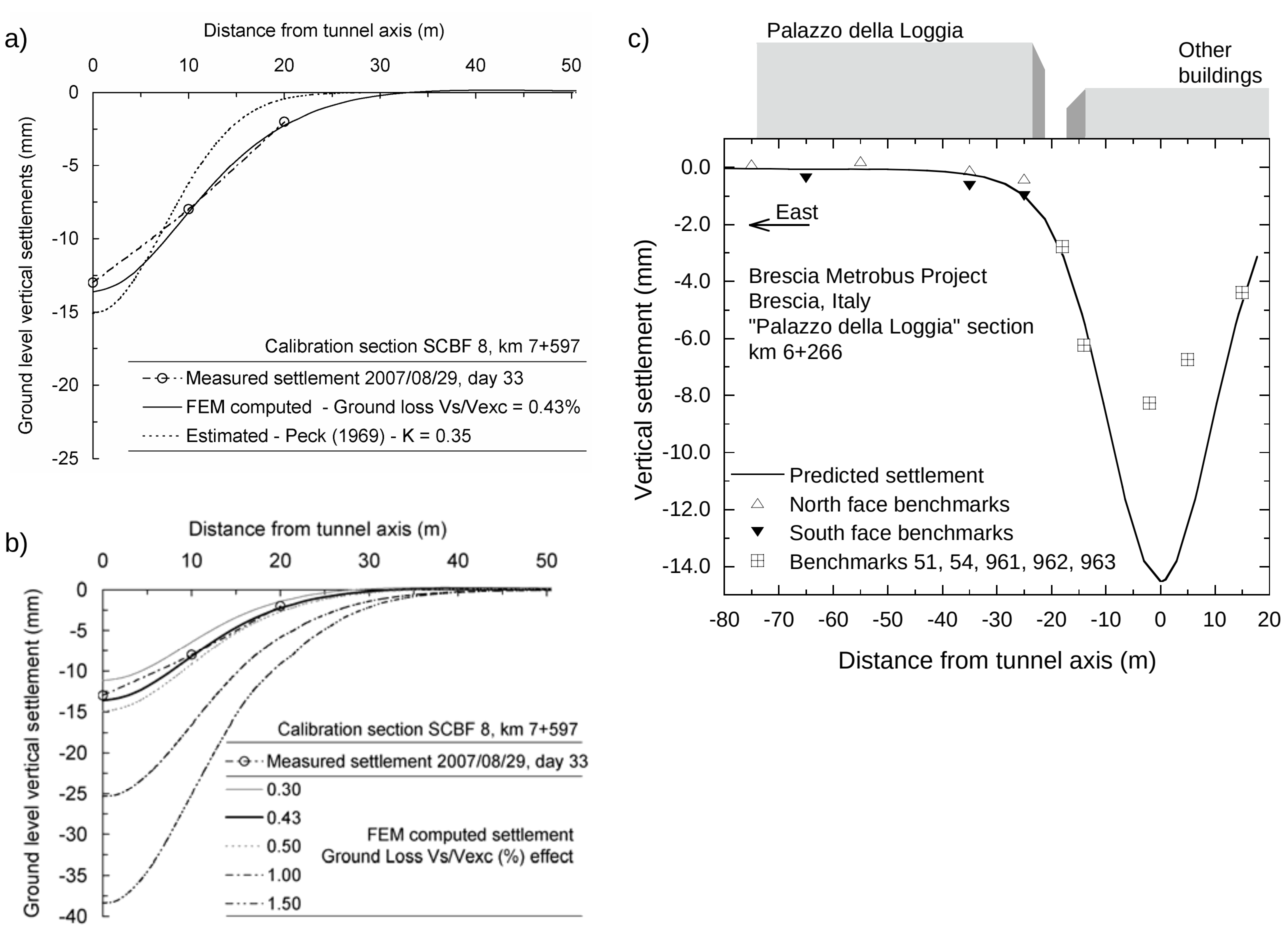

Figure 7 – Comparison of observed and computed vertical settlements at section SCBF8 (a) and effect of ground loss (b), observed and predicted vertical settlements at Palazzo della Loggia (c)

Acknowledgments

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5. References

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