COMPARATIVE EVALUATION OF CALCULATION METHODS FOR TUNNEL INDUCED SURFACE SETTLEMENTS

Attila Szepesházi

Budapest University of Technology and Economics (BME), MSc student
Budapest, Műegyetem rkp. 1, 1111, Hungary

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INTRODUCTION

The tunnelling works of the 4th metro line of Budapest has been finished in 2010. A comprehensive monitoring system has been operated with respect to the urban environment providing valuable database for the researchers, as well. Using modern, closed faced tunnel boring machines the danger of the excessive tunnel induced settlements are usually mitigated. However, some examples (Ocak, Bilgin, 2009.) showed that the investigation of surface subsidence during the design shall not be neglected. In my BSc-thesis at BME the monitored surface subsidence between Kálvin square and Rákóczi square stations has been analysed. A short summary of this study is given here. Two cross sections of the line (no. 52+82 and no. 54+13) were chosen to test some calculation methods. On the one hand traditional techniques, such as the solution of Peck, Loganathan & Poulos and Chaiwonglek & Suwansawat were used. Furthermore 2D and 3D FE models were created to compare their results with the field measurements.

CALCULATION TECHNIQUES FOR TUNNEL INDUCED SETTLEMENTS

A short introduction of the tested calculation methods are given in the following paragraphs. According to their principles, different techniques can be grouped as stochastic-empirical, analytical and numerical methods. The following summary is given according to Suwansawat (2002).

The first group is mainly developed on the basic stochastic equations of Litwinniszyn. However, their practical use could only be possible after Peck simplified these formulas. Based on observations of tunnel projects, Peck found that the surface trough could be approximated by a Gaussian curve. The settlements trough induced by a construction of a single tunnel can be estimated by formulae (1).

$$\delta_z = \delta_{max} * e^{-\left(\frac{x^2}{2*i^2}\right)} \tag{1}$$

Where x is the horizontal distance from the centre line of the tunnel, i is the x coordinate of the inflection points of the curve, δ_{max} is the maximum settlement located at the centreline above the tunnel. Using this equation the surface trough can be presented by determining two unknowns (i and δ_{max}).

Cording and Hansmire observed that (primarily in clayey ground) the volume of the settlement trough is approximately equal to the volume loss during the tunnel construction. Therefore, the volume loss (V_L in %) can be defined by equation (2), where D is the diameter of the tunnel and V_δ is the volume of the settlement trough which can easily be calculated by a simple formulae using i and δ_{max}.

$$V_L = V_\delta / \left(D^2 * \frac{\pi}{4}\right) \tag{2}$$

Using these equations the original formulae of Peck can be transformed to determine the surface trough by i and V_L. The horizontal distance of the points of inflection can be approximated by the empirical formula of O'Reilly and New. The volume loss mainly depends on the applied tunnelling technique and the quality of the ground environment. Considering these factors a conservative estimation can always be given for its value. At the pre-design phase of Metro4 project the volume loss was presumed as 1% considering the parameters of the selected EPB machine and the typical ground conditions. Rowe et al (1983, 1992) published the so-called gap method for the more proper calculation of the volume loss. Using this solution the 3D ground movements at the tunnel face, the over-excavation around the circumference of the shield and void arise from the difference between the diameter of the lining and the shield can be taken into account as the sources of the volume loss and therefore the sources of the settlements.

Analytical solutions based on the examination of the homogenous elastic half space have been published, as well. The techniques of Sagaseta, Verruijt & Booker or Loganathan & Poulos could be mentioned here. These techniques are developed using different assumptions but the majority of them, similarly to the method of Peck, use the volume loss as the most important input parameter. Recently, another solution has been published by Chaiwonglek & Suwansawat (2009) which does not contain the volume loss as an input parameter. It works with parameters describing the quality of the construction method such as the face pressure or the grouting pressure.

The detailed groups can be called as conventional techniques. Nevertheless, numerical methods are pushed forward in the tunnelling, as well. It has to be emphasized, when the tunnel induced settlements are calculated by 2D finite element analysis, the volume loss has to be incorporated to the model. Usually, the softwares are able to handle it by defining an equivalent contraction for the finite elements of the tunnel linings. Using 3D analysis some sources of the volume loss can be directly built in the model but others have to be taken into account by the contraction of the lining. On the other hand the application of modern constitutive models makes it possible to make calculations in case where the simple, conventional techniques could be hardly accepted. Franzius (2003) summarized the experiences with the computational calculations for tunnel induced subsidence. He established that the stiffness parameters' depth-dependency and the soil behaviour in the range of small strains should be taken into account for the proper calculation of surface subsidence, as well.

In my study the traditional techniques of Peck, Loganathan & Poulos and Chaiwonglek & Suwansawat has been tested. The Department of Geotechnics at BME and UVATERV Engineering Consultants Ltd. made me possible the work with the PLAXIS v.8.2. and PLAXIS 3D Tunnel FE softwares to create plain strain and 3D FE models. Instead of a conservative approximation the method of Rowe et al. (1992) was applied to find the value of the volume loss.

PARAMETERS INFLUENCING THE EVOLUTION OF SURFACE SETTLEMENTS

In Table 1 I have summarized the more important factors that should be considered for the correct calculation of tunnel induced settlements. In addition, Table 1 contains how these factors could be assessed for the examined area of Metro4 project and taken into account by the different calculation methods. These factors are collected into 3 groups: parameters depending on the construction method; parameters connected to the alignment and the geometry of the tunnel; parameters representing the geological, hydrological and geotechnical properties of the ground environment.

FINITE ELEMENT MODELLING

Using PLAXIS v.8.2. two, partly different 2D models with plain strain assumption were created. Besides a 3D FE model were made with PLAXIS 3D Tunnel module. A summary about the material models and the some details of the models created are given here.

Table 1 : Parameters influencing the evolution of surface settlements

Factors influencing the tunnel induced settlements		Assessment of the influencing factors for the examined area of the Metro4 project	The gap method (Rowe et al., 1992)	2D analysis	3D FE analysis
Parameters of construction method	Confinement pressure at the tunnel face	According to the confinements pressure plans the face pressure at the top point of the tunnel was between 190-200 kPa in the examined section.	can handle it as an input parameter	can handle it through the volume loss	It can be directly defined in the model as a distributed load.
	Overcutting bead of the shield	According to the shield plans this factor is negligible.	can handle it as an input parameter	can handle it through the volume loss	can handle it through the volume loss
	Steering problems	The use of an automatic steering system eliminate this source of subsidence.	can handle it as an input parameter	can handle it through the volume loss	can handle it through the volume loss
	Tail void, grouting efficiency	According to the shield plans the height of the tail void was 250 mm while the grouting efficiency was approximated as 95% considering the construction method statement of the mortar injection and the ground properties.	can handle it as an input parameter	can handle it through the volume loss	can handle it through the volume loss
	Deformation of segmental lining	The 30 cm thick segments of concrete suffers negligible deformation.	neglect this factor	Conventional methods neglect this source of subsidence while 2D FE analysis can count it by the defined material model of the lining.	can count it according to the material model of the lining
	Tunnelling penetration rate	The tunnelling progress was quite rapid and permanent in the examined area.	neglect this factor	neglect the influence of this phenomenon	neglect the influence of this phenomenon
Tunnel geometry and alignment	Tunnel depth and radius	The outer radius of the tunnel is 5,8m while the tunnel depth is 17,5 and 16,1m in the examined cross-sections.	can handle it as an input parameter	can handle it as an input parameter	can handle it as an input parameter
	Distance from the launching station	The reduction of the confinement pressure for the protection of the segmental lining was not necessary in the examined sections as they are far enough from the Kálvin station.	can handle it through the confinement pressure as that is an input parameter	can handle it through the volume loss	can handle it through the confinement pressure
	Construction sequence of twin tunnels	The right tunnel line was being constructed first.	neglect this parameter	Conventional methods neglect this parameter while 2D FE analysis are able to count the construction sequence.	the construction sequence can be incorporated
	Distribution and stiffness of surface structures	Mainly 3 and 4 storey, old building can be found in the examined area.	can handle only the load of the surface structures as an input parameter	Conventional methods handle it through the volume loss. With simplifications the stiffness of the surface structures can incorporated, as well.	the weight and by simplifications the stiffness can be incorporated, as well
Characteristics of the ground environment	Geological, geotechnical properties	The geological, geotechnical, hydrogeological expertise produced by GEOVIL Ltd. makes it possible to create a detailed soil model including the groundwater properties, as well.	can handle it as a few conventional parameters as input parameters	Conventional methods handle it through the volume loss and some, mainly empirical parameters characterizing the ground environment. 2D FE analyses handle it through the soil model defined.	can handle it through the soil model defined
	Groundwater properties	The applied TBM could balance the groundwater pressure, the influence of water outflow on the settlements are negligible.	can handle the water pressure as an input parameter	Conventional techniques handle it through the volume loss while in 2D FE analysis the groundwater level can be defined directly.	the groundwater level can be defined directly

Material models

The stratification of the construction area is the following. The 0.5-2.5 m thick fill overlies the 9.7-11.0 m thick Quaternary Holocene beds. The top layers of this Holocene formation are mainly a silty sand stratum while sandy gravels are in the bottom. The top of the groundwater is usually reaches the upper regions of the Holocene beds. The tunnels cross the 13-15 m thick, inhomogeneous Miocene strata beneath the Holocene formation. The thick, underlying Oligocene beds were incorporated in the calculations, as well.

The inhomogeneous fill sits above the basement level of the surface structures in both examined sections. Therefore, it is ignored in the calculations. In case of the Holocene stratum the application of linear elastic soil model is adequate. On the contrary the Miocene and Oligocene beds were calculated using hardening soil model taking into account the unloading effect of the tunnel excavation. Table 2 shows the applied values for the material models in section number 52+82. These values were average values of the very deviating soil properties of the inhomogeneous beds given in the original geotechnical report produced by GEOVIL Ltd. The tunnel linings and the shield cylinder were modelled with simple linear elastic material model. Its parameters (Table 3) could be defined by the original plans of the corresponding structures.

Table 2 and 3: Soil model parameters (on the left); Structural model parameters (on the right)

52+82 cross-section	**Holocene silty sand**	**Holocene sandy gravel**	**Miocene bed**	**Oligocene bed**
Material model	Mohr-Coulomb model		Hardening soil model	
γ_t [kN/m^3]	18,00	20,00	19,00	20,00
γ_{sat} [kN/m^3]	20,00	22,00	21,00	22,00
φ [°]	13	34	30	30
c [kPa]	25	0	60->220	220
E [kN/m^2]	5500	18000	100000	100000
ν [-]	0,35	0,30	0,40	0,35
E_s [kN/m^2]	8827	24231	214286	160494
E_{50} [kN/m^2]	-	-	214286	160494
E_{ur} [kN/m^2]	-	-	642857	481481
m [-]	-	-	0,9	0,7
thickness [m]	4,20	6,00	13,20	-

	Tunnel lining	**Shield cylinder**
Material model	Elastic	Elastic
EA [kN/m]	11100000	40000000
EI [kNm^2/m]	83250	133333
ν [-]	0,2	0,3
w [kN/m/m]	24	36

2D FE models

Figure 1 shows the 2D finite element model with the mesh of section 52+82 in the initial phase and the layout of the model in the final stage. The equivalent contraction purposed to model the influence of the volume loss were calculated by the gap method. In section 52+82 its value was found 0,6% while in 54+13 only 0,45%.

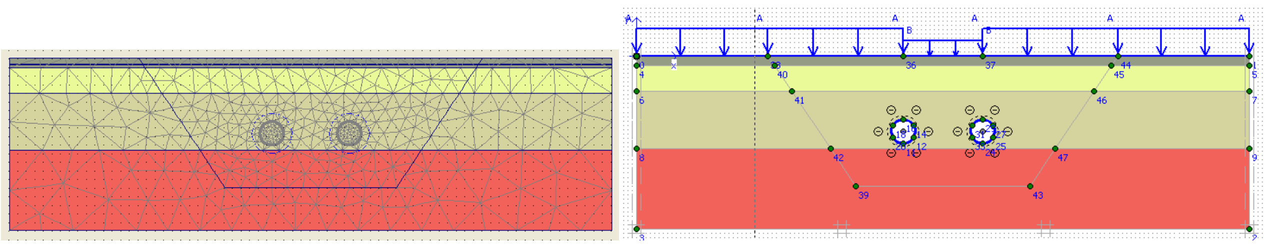

Figure 1: Section 52+82 – Finite element mesh on the left and the final construction stage and the surface loads on the right

An advantage of this method published by Rowe et al. (1992) is that the volume loss component arising in front of the tunnel face, around the shield cylinder and at the tail void can be separated. Two version of the 2D model was created. In the first version the excavation, the construction of the linings and the contraction were activated in the same stage. In the second version the excavation step, finite elements of the shield cylinder and the volume loss originated from the tunnel face and from the shield circumference were activated first. Then the shield properties were changed for the lining properties and the contraction equivalent with the tail void was applied.

3D FE models

The module of PLAXIS 3D Tunnel makes it possible to work with models built up by the longitudinal extrusion of 2D models. The frequency of the cross sections along the longitudinal axis must be chosen. Between these cross sections it is feasible to change some settings, such as the soil parameters, the surface loads, etc. The frequency of the cross sections determines the possible steps of the excavation progress, as well.

Suwansawat (2002) observed that the ground movement usually starts about 30 m ahead the tunnel face and stops about 30 m behind the shield tail. According to that, it would be necessary to model about 60-70 metres of tunnelling process to obtain the total settlement in one cross section. In addition, the analysed cross section must stand far enough from the model boundaries to avoid their influences. Considering these the size of the whole model should be about 40m×140m×140m. Using the appropriate mesh size, such model could be hardly calculated with current computer facilities due to the excessive number of finite elements. That is why some simplifications were required. Only one half of a single tunnel was modelled and only a single 1,5 meter long excavation step was analysed. Therefore, the total displacement of a section could be obtained by summing up the settlements hailed from the examined excavation step in cross sections appointed 1,5 m far from each other. The length of 1,5 m has been chosen as it is the length of one segmental lining ring. Thereafter, the total settlement of a single tunnel could be found by the reflection of the settlements to the centre line of the tunnel and by the superposition of the troughs induced by the adjacent single tunnels. As it can be seen in Figure 1 the surface loads are not fully consistent. Therefore, the utilization of the symmetry plane are not totally correct, however, the surface loads are only estimated values and their effect on the ground movements is almost negligible.

On the tunnel face a distributed load equivalent with the face pressure values was defined. The plate elements along the tunnel circumference in 7,5 metre length behind the face have the properties of the shield cylinder. Behind these, the plate elements have the material properties of the tunnel linings. One construction stage includes the excavation of the tunnel face, the penetration of the shield and the erection of a new lining ring. The 3D model of section 52+82 can be seen on Figure 2.

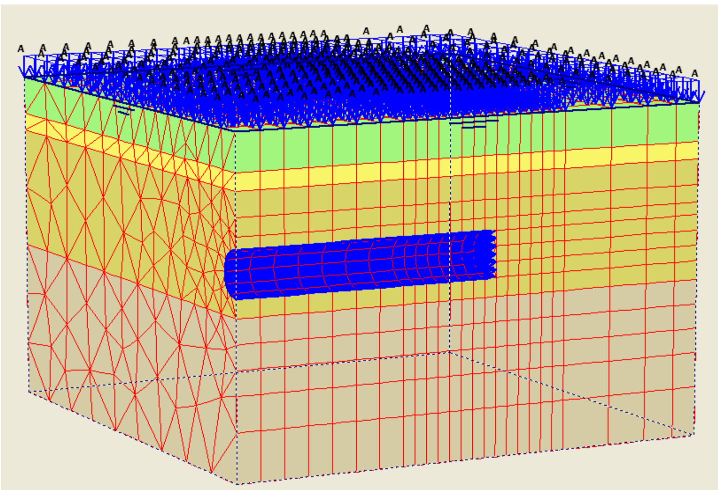

Figure 2: Section 52+82 - The analysed phase and surface loads

The definition of contraction for the 2D models was a simple task but for the 3D models some considerations must be made. The applied contraction was separated for 3 components. The volume loss arising ahead the tunnel face has not been taken into account due to the fact that the tunnel face and the appropriate confinement pressure have been included as a distributed load. The volume loss originated from the shield circumference was divided equally for the finite elements of the shield cylinder. The volume loss hails from the diameter difference of the shield and the lining reduced by the mortar injection was defined for the first element ring of the tunnel lining. This way all the tunnel segments suffered the appropriate value of contraction calculated by the gap method.

RESULTS OF THE FE CALCULATIONS

The two, partly different version of the 2D FE models produced the same results. Figure 3 shows the total displacement calculated with the first version in section 52+82. It can be noticed that the movements above the tunnel on the right, which was constructed first, are slightly higher compared to the left tunnel. This phenomenon matches with the field observations described in several literatures. Section 54+13 showed similar but slightly more asymmetric surface trough due to the inconsistent surface loads.

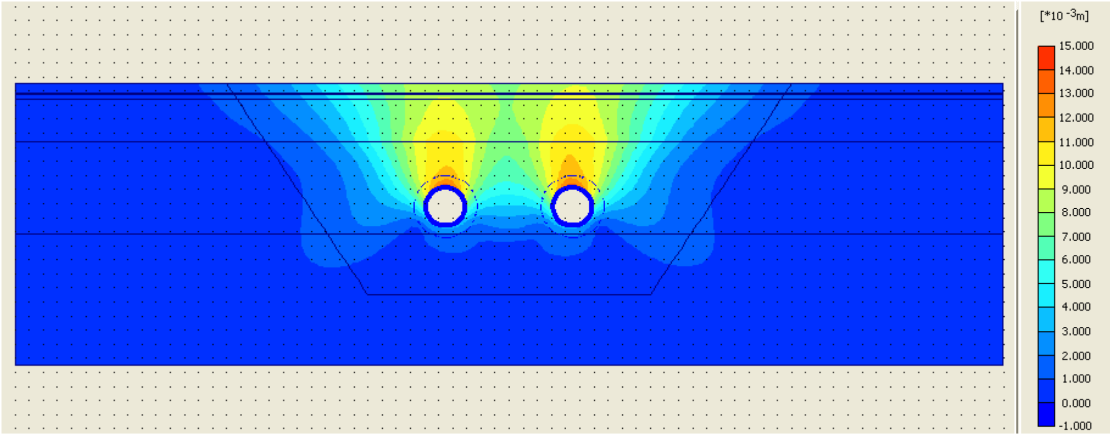

Figure 3: Section 52+82 - The total displacements at the final stage

Figure 4 and 5 show the total and vertical displacement resulted of one excavation step in section 52+82. In Figure 4 the yellow shades presents the larger displacements originated from the expansion of the tunnel face and from the diameter difference of the lining and the shield cylinder.

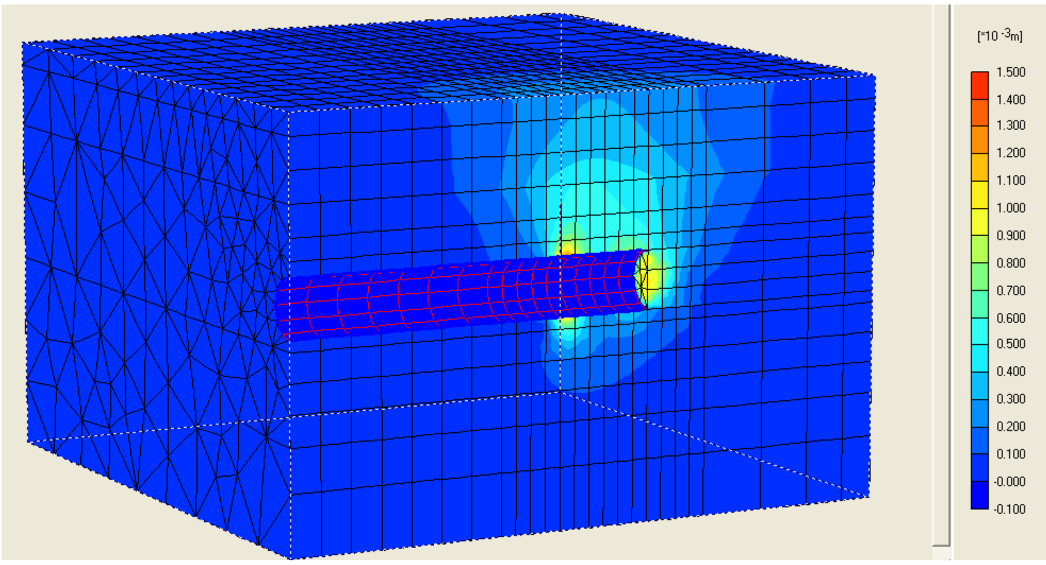

Figure 4: Section 52+82 – Total displacements at the analysed stage

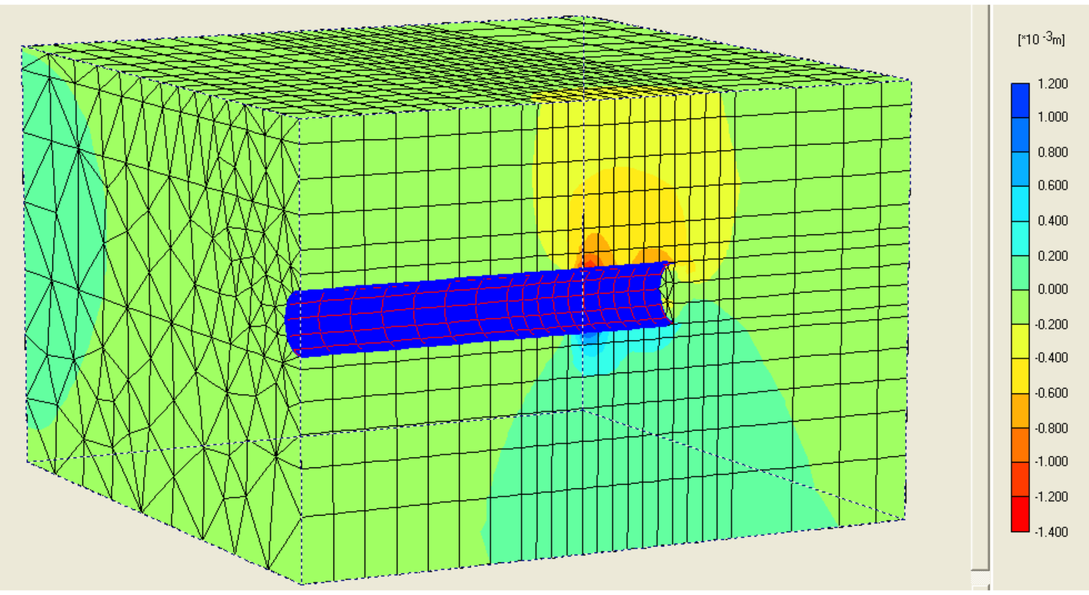

Figure 5: Section 52+82 – Vertical displacements at the analysed stage

COMPARATIVE EVALUATION OF THE CALCULATED AND THE MEASURED SURFACE TROUGH

Figure 6 and 7 present the calculated and monitored settlement troughs in the analysed sections. Figure 6 shows that the traditional methods of Peck, Loganathan & Poulos and the 2D FE techniques provided practically the same settlement curve. The 3D FE calculations gave slightly lower trough what seems to be reasonable as it take into account the 3D stiffness of the lining and the 3D arching effect, as well. However, the superposition of the settlements originated from only one excavation step brought some uncertainty with itself. The monitored data fits well to these curves but it is hard to determine whether the 2D or 3D results are more accurate. The method of Chaiwonglek and Suwansawat resulted in about double settlement values compared to the other solutions. Its reason is possibly that this technique is quite sensitive for the Young's modulus of the soil which was one of the most varying parameter in the examined area. The analysis of section 54+13 resulted similar consequences. Nevertheless, the curves in Figure 7 shows larger deviation what can be imputed to the lower settlement values.

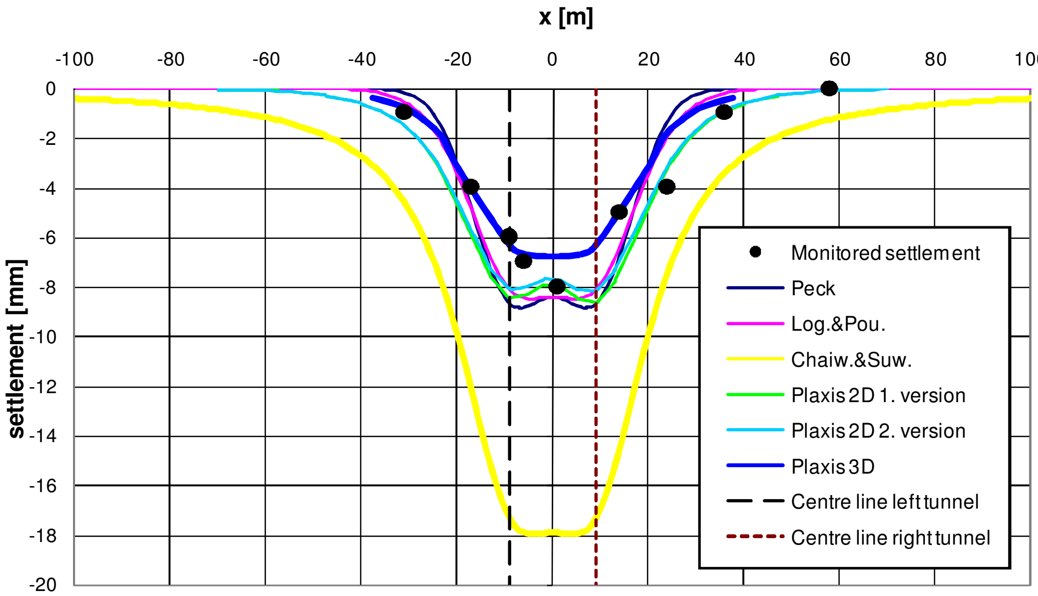

Figure 6: Section 52+82 – Comparison of the calculated and measured settlements

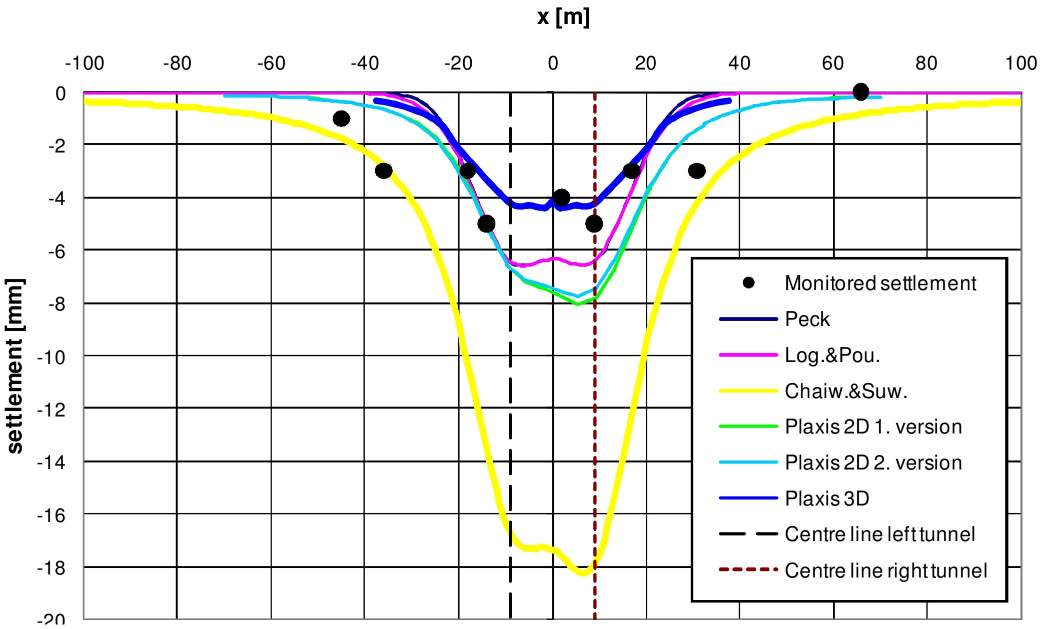

Figure 7: Section 54+13 – Comparison of the calculated and measured settlements

CONCLUSIONS

It can be stated that generally there is no reason to use 3D models for the calculation of tunnel induced settlements with respect to the necessary efforts. In addition, the necessary simplifications and the application of larger mesh elements can question the growth of its accuracy. However, when we need more information, such as we have to examine the face stability, the loads in the linings or the analysed tunnel construction crosses sensitive areas, the application of 3D analysis can be rewarding. As it can be seen in Figure 6 and 7, all the 2D techniques give the same settlement curve except the quite recent method of Chaiwonglek and Suwansawat. Therefore, it looks reasonable to endeavour the more accurate estimation of the volume loss. Some input parameters of the gap method, such as the efficiency of the mortar injection or the openness of the shield face, strongly affect the calculated value of the volume lost but for these only a rough estimation can be given.

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