PREDICTION AND EVALUATION OF THE SURFACE SETTLEMENT ABOVE EPB SHIELDS

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ABSTRACT: The aim of this paper is numerical modelling of running tunnels of Prague metro V.A excavated by EPB shields and evaluation of the surface settlements associated with realized excavations. Program Plaxis 2D based on finite element method was used to generate numerical models. Also analytical solutions were applied. Calculated values of surface settlement were compared with the results of the geotechnical monitoring and back analysis was performed to tune generated models.

1. INTRODUCTION

Currently, due to the limited space in the urban transport systems, the development is mainly due to the construction of underground structures. There is a need for sophisticated underground works, such as the construction of tunnels, underground parking and other facilities, which often have to be built under the existing urban structures in some cases, of historical value.

There are problems related to the impacts of the construction and operation of tunnels in urban environments. These problems manifest themselves in the form of ground surface settlement. Excessive settlement can cause damage to surface and underground facilities. The state of the old buildings can be affected even by only small settlements. The estimation of the ground surface settlement in urban areas is one of the problems to be solved in the design of tunnels.

The methods for assessing soil settlements in the construction of tunnels can be classified into three groups: empirical, numerical and analytical. These methods are widely used in practice to evaluate the ground deformation which arises in the construction of tunnels. Choosing the appropriate method depends on the particular circumstances and complexity of the problem.

2. ANALYTICAL CALCULATIONS

2.1 FORMULAS BY PECK AND SCHMIDT

Schmidt-Peck integrating observed data from 20 tunnel projects found that surface subsidence curves approximately follow a one path curve. The equation used by Peck and Schmidt [1] to specify the settlement profile is:

$$S = S_{max} \exp^{\frac{-x^2}{2i^2}} \qquad (1)$$

Where:

Smax is the maximum vertical settlement over the centreline of the tunnel.

S is the vertical settlement over the centreline of the tunnel.

x is the distance from the tunnel axis to the settlement point (calculated with the horizontal direction)

I is the parameter which defines the width of the settlement trough.

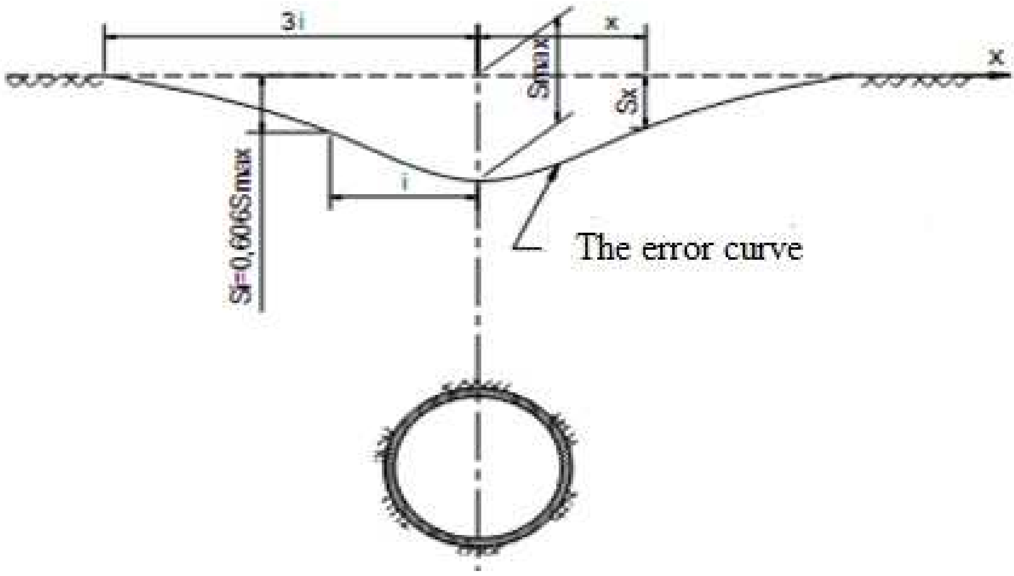

Figure 1: Soil surface settlement represented by the error curve [1]

2.2 FORMULAS BY O'REILLY AND NEW

O'Reilly and New [2] developed general equations for both cohesive and cohesionless soil using the effective width (i) and the soil constant (K) on the basis of the three dimensional equation was proposed by Attevell. According to O'Reilly and New:

$$i = K.Z \qquad (2)$$

Where K =0.4 – 0.7 for hard and soft clay, respectively, and the value K = 0.25 for sands and Z is the depth of the tunnel centre.

$i = 0.43Z + 1.1m$ for cohesive soil.
$i = 0.28Z - 1.12m$ for cohesionless soil.

Moreover, in the case of multi-layered strata (N layers), the trough width is given as

$$i_n = K_1.Z_1 + K_2.Z_2 + K_3.Z_3 + \cdots + K_n.Z_n \qquad (3)$$

For twin tunnels:

$$S = S_{maxA}\exp\left[\frac{-\left(x+\frac{L}{2}\right)^2}{2i^2}\right] + S_{maxB}\exp\left[\frac{-\left(x-\frac{L}{2}\right)^2}{2i^2}\right] \qquad (4)$$

Where: L- the distance between the two tunnels.

Furthermore, O'Reilly and New proposed the relationship between the horizontal and vertical components of displacement:

$$H_{(y;z)} = \frac{y}{z}.S_{(y;z)} \qquad (5)$$

Where $H_{(y;z)}$ and $S_{(y;z)}$ are the horizontal and vertical components at a transverse distance y and at a vertical distance z from the tunnel axis respectively.

2.3 FORMULAS BY CORDING AND HANSMIRE

Cording and Hansmire [3] at the University of Illinois are Pecks successors. They used the properties of the normal distribution curve by Peck and Schmidt (2). However, they modified the trough relation by using a vertical angle β, which is the angle between the vertical line and the line drawn from the spring line to the edge of the surface trough. Fig.11 relates β to different ground types.

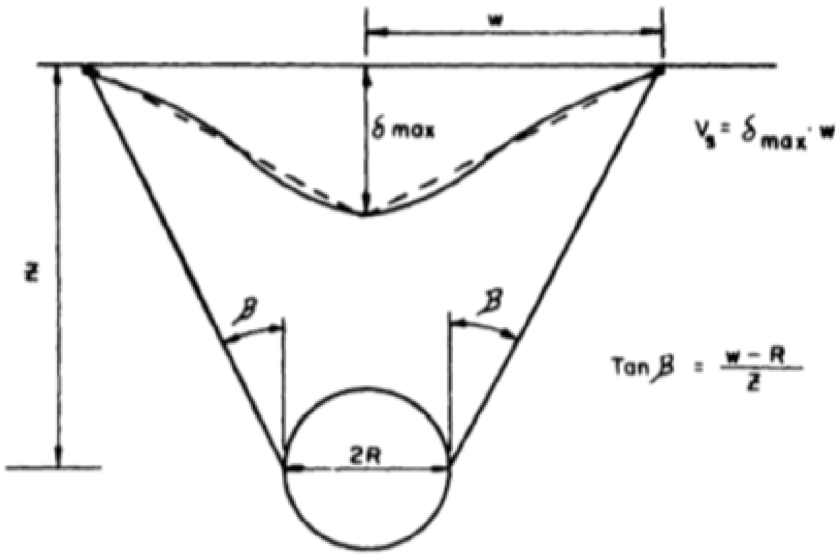

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Figure 2: Relation of β to through width [3]

Here, w is the half width of the base of the triangular trough $w = \pm 2.5i$. The correlation of (i) with the tunnel radius, depth, and soil type is shown in the Fig.12 below.

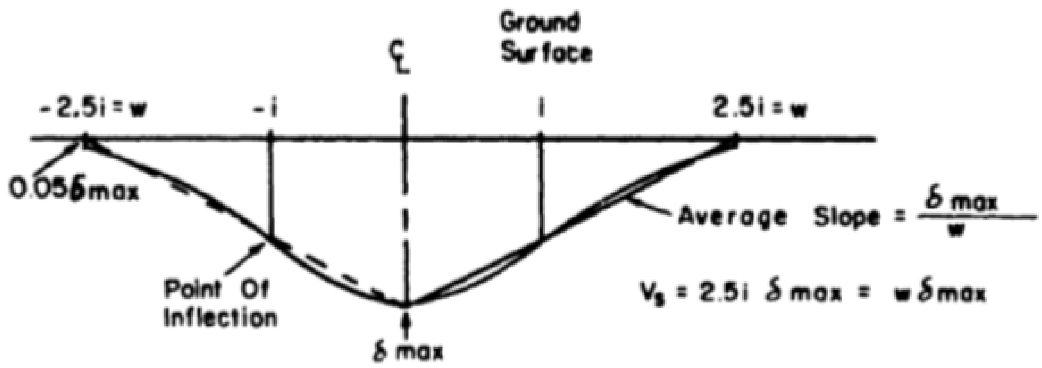

Figure 3: Width of the settlement trough, [3]

3. NUMERICAL MODELLING

The finite element method is the most common method of estimating surface subsidence during the tunnelling process. But it also does not mean that we underestimate the difficulty and complicated factors in model calculations, which has been emphasized by O'Reilly and New, who say that: geological problems during tunnel construction have proven to be very difficult to model using finite element because of their complex nature...

When modelling and predicting the surface subsidence development by geotechnical software, input data are required, such as the tunnelling dimension size, the tunnel depth, geological conditions, ground water, etc. Currently, in the world there are a lot of computing software applications for geotechnical analysis, such as Plaxis, Mises, Z-Soil, GEO, etc. The Plaxis software was used in this research to assess the surface settlement caused by TBM tunnelling.

Variant I: tunnel construction by β-method

The *β-method* is various methods for the analysis of tunnels constructed. The idea is that the initial stresses p_k acting around the location where the tunnel is to be constructed are divided into a part $(1-\beta).p_k$ that is applied to the unsupported tunnel and a part β p_k that is applied to the supported tunnel (Fig. 4). The β -value is an 'experience value', which, among other things, depends on the ratio of the unsupported tunnel length and the equivalent tunnel diameter.

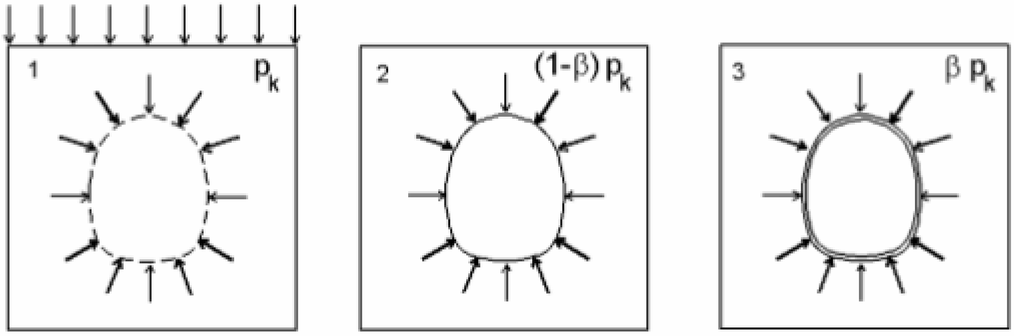

Figure 4: Schematic representation of the β –method, [5]

Variant II: Applying contraction of tunnel lining

The contraction method will be used for simulation of ground volume loss due to the tunnel construction by TBM shield. In this method a contraction is applied to the tunnel lining to simulate a reduction of the tunnel cross-section area. The contraction is expressed as a percentage, representing the ratio of the area reduction and the original outer tunnel cross-section area.

4. RESULTS OF MODELLING

The second ground surface settlements at the chainage km 15.3 was analysed and evaluated. The tunnel depth at the position is -15.6m in the clayshale layer under two layers of deluvial sediments and loessial soil.

Table 1: Geological parameters of Dejvická - Bořislavka at the cross-section of km 15.3

Parameter	Symbol	Deluvial sediments	GT2-Qe	GT3-Qd	GT6-OBz	Unit
Dry weight	γ_{unsat}	18	19	18	25	(kN/m^3)
Wet weight	γ_{sat}	19	21	20	26	(kN/m^3)
Young's modulus	E	8.10^3	10.10^3	15.10^3	70.10^3	(kN/m^2)
Poisson's ratio	ν	0.4	0.35	0.35	0.28	
Friction angle	φ	20	23	25	25	^{0}
Cohesion	C_{ef}	25	12	15	35	kN/m^2
Dilatancy angle	ψ	5	5	5	5	^{0}
Interface strength reduction	R_{inter}	1	1	1	1	

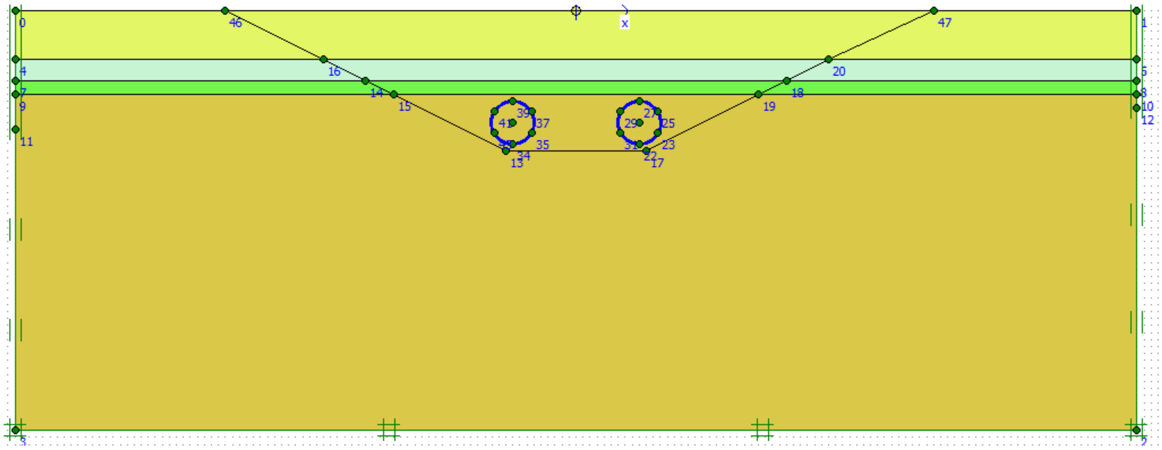

Figure 5: Geometry of the tunnel model

The twin tunnel considered in this case has a diameter 5.08m and is located at an average depth of 15m. The upper 15m consist of 3 different soils. The y_{max} parameter defined as 0m and the y_{min} as -65m, see Fig. 5. The distance between the axis of the two single tunnels is18m.

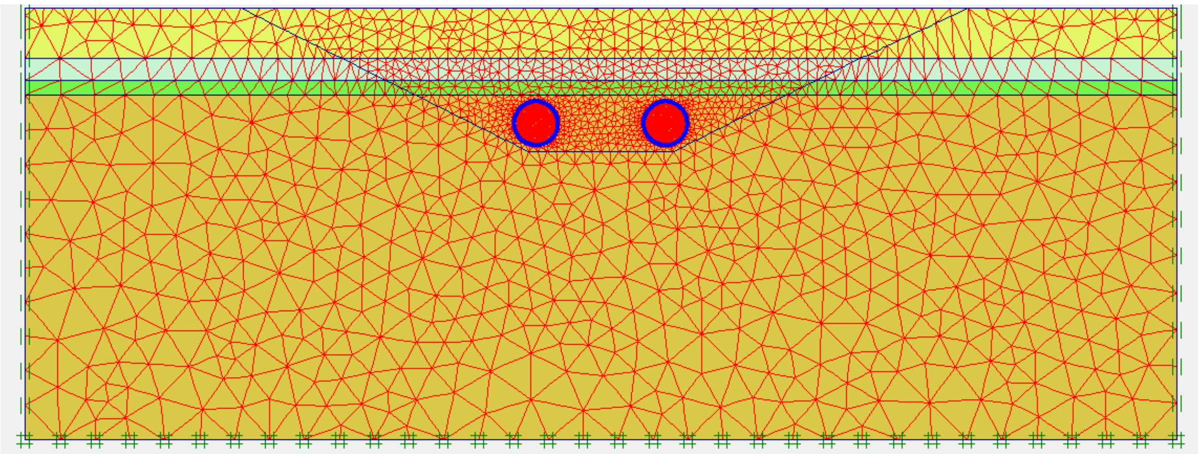

Figure 1: Generated mesh for single tunnel

In this case the global coarseness parameter very fine will be accepted and the option refine line and refine cluster are also used for the refinement of the ground surrounding the tunnel and the cluster inside the tunnel (Fig. 6). Results of modelling are presented on Fig.7 -12.

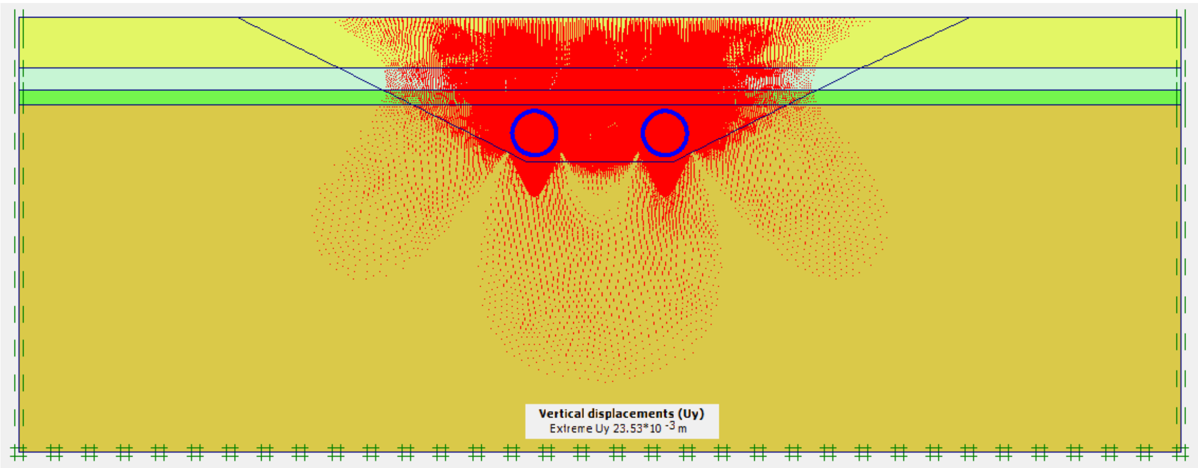

Figure 7: Vertical displacement (arrows) – variant I

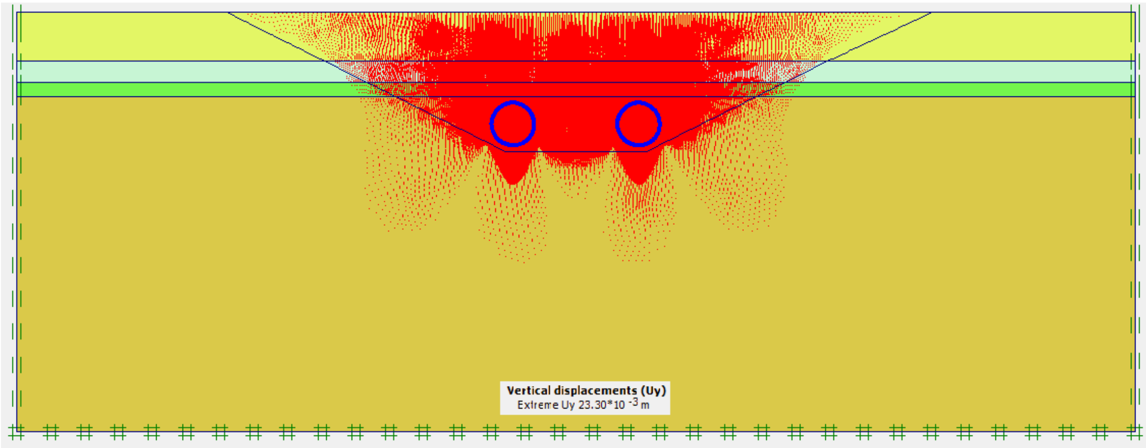

Figure 8: Vertical displacement (arrows) – variant II

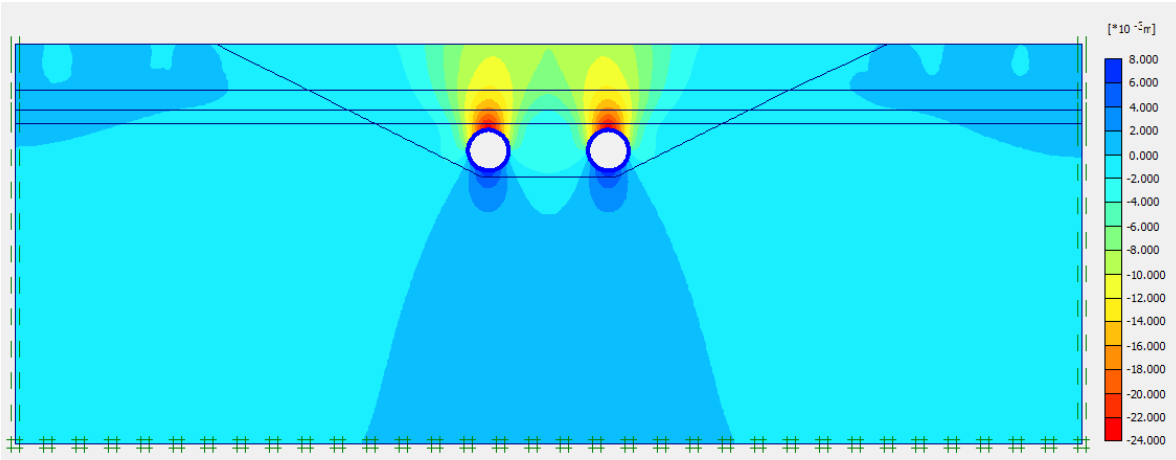

Figure 9: Vertical displacements (shading) – variant I

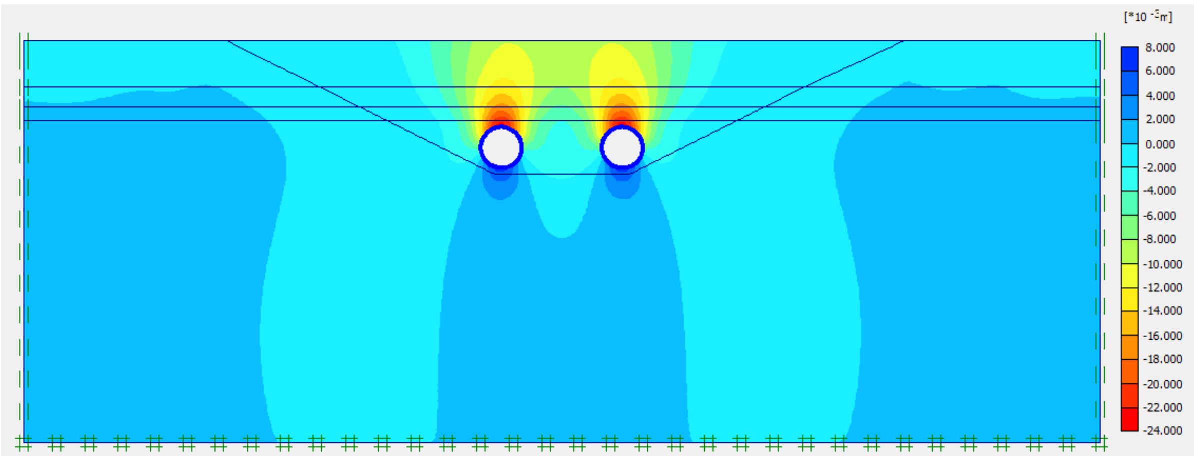

Figure 10: Vertical displacements (shading) – variant II

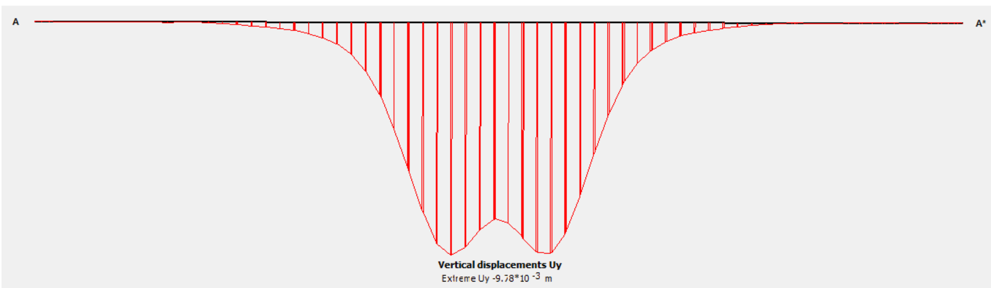

Figure 112: Surface settlement profile of cross section A-A* - variant I

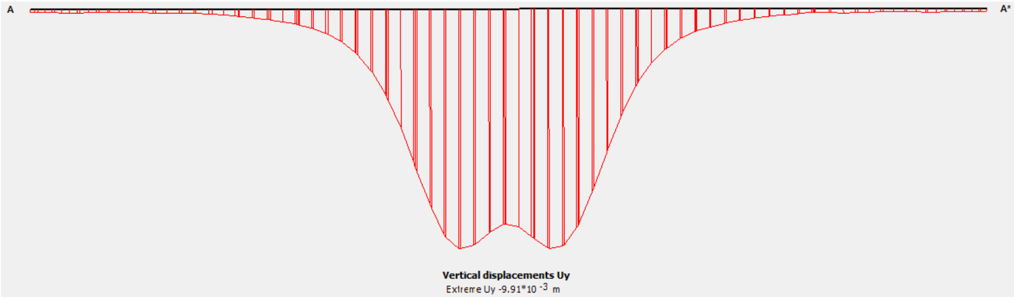

Figure 12: Surface settlement profile of cross section A-A*

5. MODEL VERIFICATION BY MONITORING

According to the result from the BARAB database at the position of 15.317km, only four points were surveyed (Fig.13), so that the finger only represents a part of the settlement trough. The maximum ground surface settlement at this section is 4mm when the first EPB is passing and 9.7mm when the both EPB are passing.

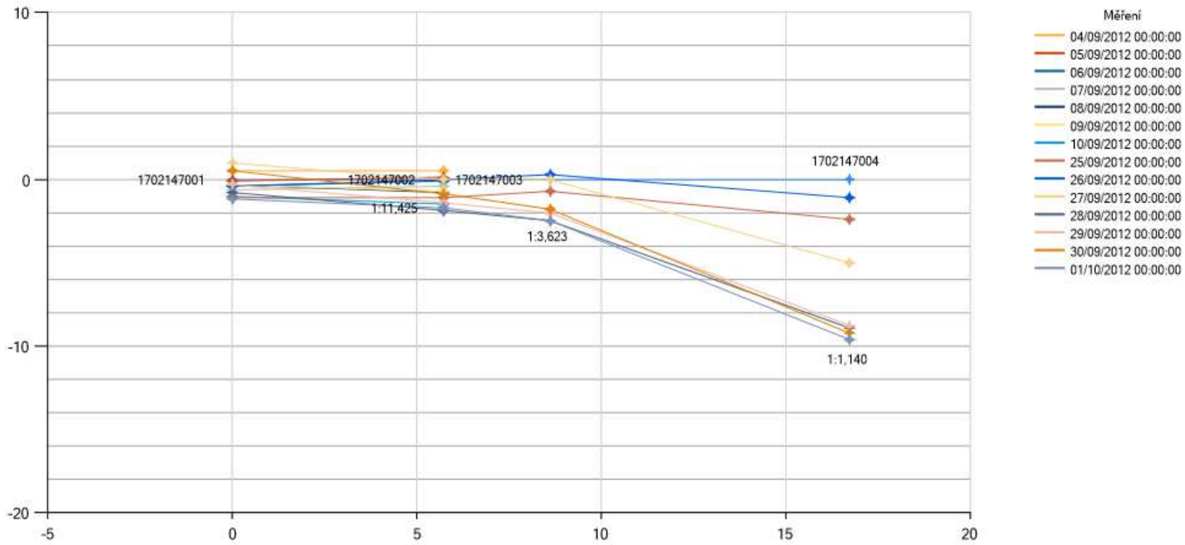

Figure 13: Cross section of ground surface settlement at the position of 15.3 km [7]

According to the result of the volume loss (Z) calculated from the settlement troughs for the range of measured settlements (S_{max}) (section 5.5), at this section the volume loss Z = 0.65 when the both EPB are passing. On the basis the value loss (Z) selected for the calculation ground surface settlement calculation by analytical methods Z = 0.65% for a twin tunnels. The value of ∑Mstage was selected for the ground surface settlement calculation by the PLAXIS software by the β-method of ∑Mstage = 0.5. For the contraction method, the value contraction increment is 0.6 for twin tunnels. The following is the graph indicates the shape of the settlement trough of the different methods and the result of the monitoring.

According to the results of the analysis above we can conclude as follows:

The calculated results show in the chart above, the width of the settlement trough "i" is calculated by the method of analysis being similar to about 80m. The width of the settlement calculated by Finite element modelling (PLAXIS software) is larger than the result by analytical methods

The results are calculated by analytical methods and by FEM for larger results than the actual result. But there is a relatively small deviation, which proves that the analytical methods and FEM are very reliable for the prediction of surveys of ground deformations.

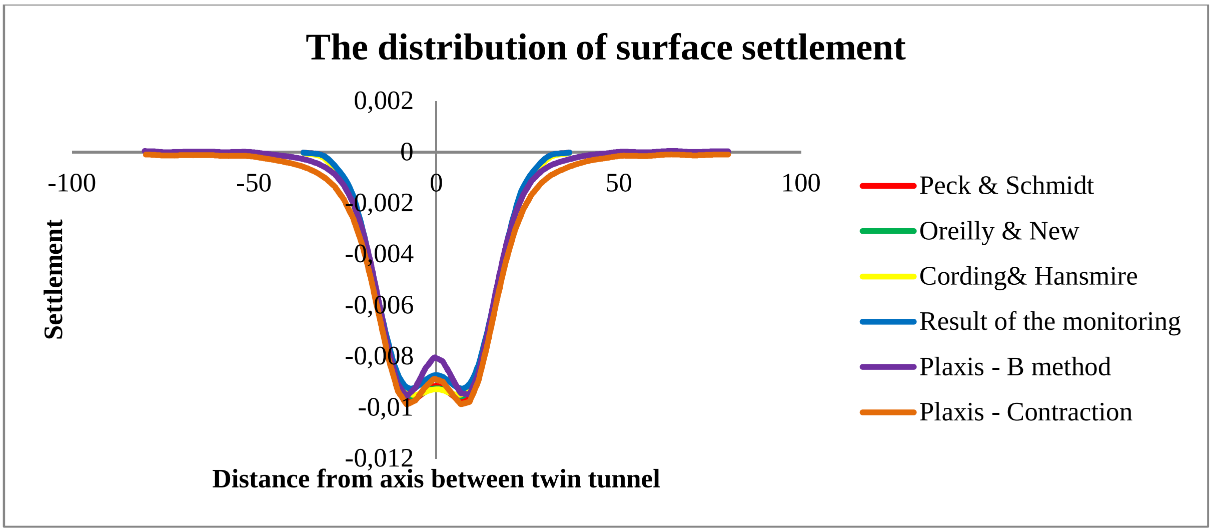

Figure 14: Surface settlement – comparison of twin tunnel results

6. CONCLUSION

The presented study is focused on the prediction of the surface settlement caused by excavations using EPB shields. Basic information about EPB shield tunnelling (and generally TBM tunnelling) was presented. Various analytical solutions to evaluate the impact of mechanical tunnelling on ground deformations and surface settlement were presented. Also, basic information about numerical modelling was shown.

The available tools for the settlement prediction were verified on the Prague metro, line V.A, where both running tunnels were excavated by EPB shields. The cross-section at km 15.3 was evaluated. The volume loss at the location km 15.3 was 0.65%. Finite element modelling (PLAXIS software) was utilised to model both tubes. The results of modelling were compared to the results of monitoring and the results of analytical calculations, all results match reasonably well.

7. ACKNOWLEDGEMENTS

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[7] http://www.barab.eu/

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