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VERIFICATION OF AN IMPROVED PREDICTION METHOD FOR EFFECTS OF SHALLOW TUNNELLING

Abstract

This paper has focused on verification of practical applicability of calculation methods for establishing of subsidence trough parameters related to shallow tunnelling. Both qualitative and quantitative aspect of these parameters are scrutinised by using them for solving of practical tasks and prediction accuracy of specific calculations has been verified.

Keywords

Subsidence trough, shallow tunnelling, numerical analysis, empirical approach.

Abstrakt

Obsahem příspěvku je ověření spolehlivosti praktického použití prezentovaných výpočetních postupů pro stanovení parametrů poklesové kotliny při ražení mělkých podzemních děl, pro kvantitativní i kvalitativní vyhodnocení těchto parametrů v konkrétních praktických úlohách a ověření dostatečné vypovídací schopnosti výsledků provedených výpočtů.

Klíčová slova

Poklesová kotlina, tunelování v malých hloubkách, analytická řešení, emipický přístup.

1 INTRODUCTION

The calculations for surface subsidence due to excavation of a sewer collector, Ostrava-Centre, were conducted utilising calculation methods that are specified in what follows. All principal subsidence trough characteristics have been scrutinised (maximum settlement, inflection point location, maximum subsidence slope, length of subsidence trough), and the model calculation results were assessed in parallel to those of in situ monitoring.

Quantitative and qualitative comparisons of three specific subsidence troughs were performed, namely, subsidence trough, PK 060 (kilometrage, 0.100 km), PK 260 (kilometrage, 0.752 40 km), and PK 390 (kilometrage, 1.1 km), see Fig. 1, 2, 3. The actual monitoring measurement results were provided by the firm, INSET, which had performed the measurements.

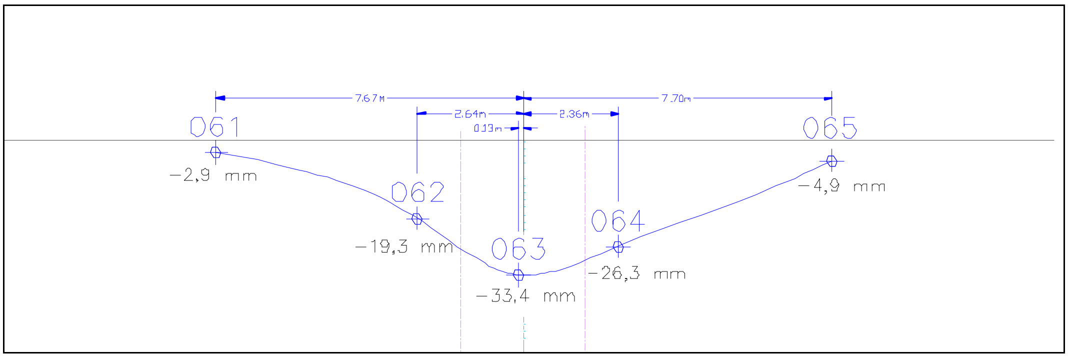

Fig.1 Subsidence trough PK 060 (courtesy INSET)

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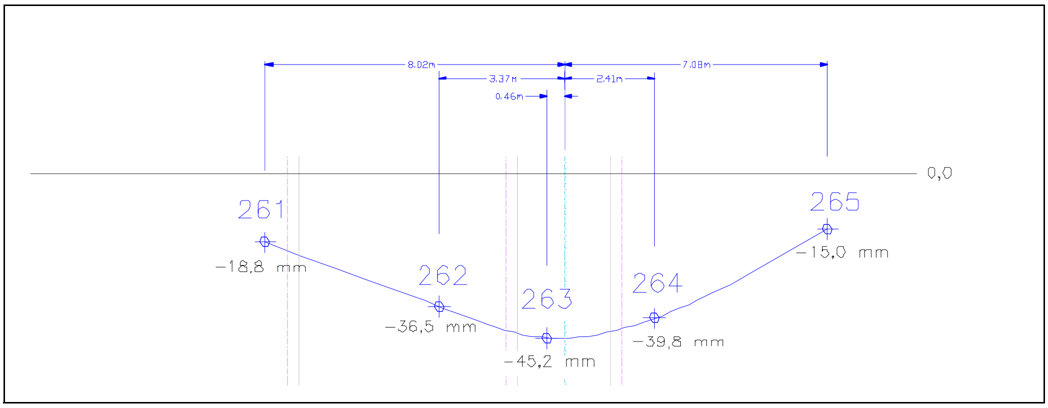

Fig.2 Subsidence trough PK 260 (courtesy INSET)

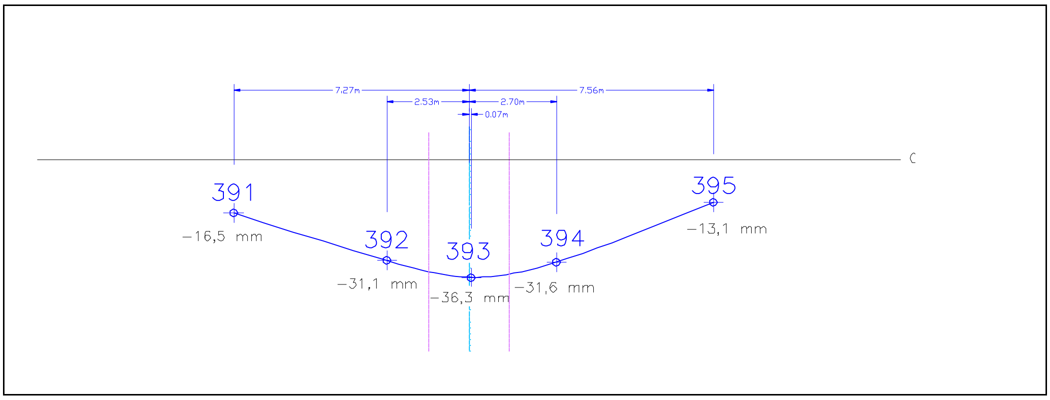

Fig.3 Subsidence trough PK 390 (courtesy INSET)

The U-shaped sewer collector is 4.5 metres high, 3 metres wide and its centre is located about 8 metres below the surface. It is predominantly excavated in sand and gravel soils. About 1/3 of the collector's vertical face has been excavated in soft or stiff clays. The backfill roof, three meters deep, consists of sand and gravel. The underground water level has been localized about 6.5 metres below surface.

The technology of manual excavation, 0.7 metres of advance, has been used for the collector's tunnelling. The excavation cavity vault is reinforced from above through the roof by a system of longitudinal concrete injections, 2.2 metres long with 0.35 metre in-between distance. In some rare instances, also reinforcement by the same method is made at sides. The primary reinforcement of the tunnel itself is made by concrete spraying (thickness, 200 millimetres) that is armoured by U-shaped truss girders, ASTA, with two layers of steel wire mesh, 100 x 100 x 6 millimetres.

The collector's geometric characteristics, depth of location, and excavation soil characteristics are given by Tab. 1 and illustrated by Fig. 4.

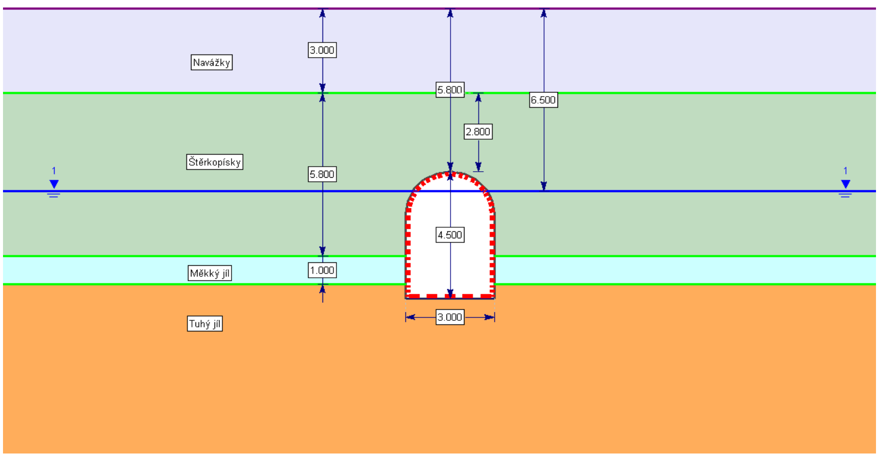

Fig 4: Collector's geometric characteristics and rock strata structuring

Parameter	Type of soil			
	Backfill	Sand and gravel	Soft clay	Hard clay
Mass unit weight (kN/m^3)	19,5	19,6	19,9	19,9
Elastic modulus, E (MPa)	8	25	4.5	18,5
Poisson's Number	0,4	0,2	0,4	0,4
Consistency (kPa)	8	3	20	30
Angle of internal friction (°)	26	31,5	21	21

Tab.1: Principal material and soil characteristics

An improved method of numerical analysis [1] and empirical methods, [5], [6], and have been used for calculations of the subsidence trough characteristics. The methods assume an excavation circular profile. For that reason, the U-shaped face of the tunnel was substituted in the calculations by a circular face of the same size with the resulting radius of 2 metres.

2 SUMMARY OF PRINCIPAL SUBSIDENCE TROUGH CHARACTERISTICS THAT DETERMINE INFLUENCE OF SHALLOW TUNNELLING ON SURFACE BUILDING STRUCTURES

Principal characteristics that determine influences of shallow tunnelling on building structures located on the surface above are:

- Maximum settlement u_{max},
- Location of inflection point i,
- Width of subsidence trough L,
- Inflection point maximum slope d_{max},
- Coefficient of maximum horizontal deformation ε_{max}.

These quantitative characteristics of subsidence troughs have been evaluated by mathematical methods that are specified in what follows. The coefficient of maximum horizontal deformation was established by utilising an approximation value [2], [6]:

$$\varepsilon_{max} \cong 0.66\ d_{max} \qquad (1)$$

3 REGRESSION ANALYSIS FOR ESTABLISHMENT OF SUBSIDENCE TROUGH CHARACTERISTICS AS BASED ON MONITORING DATA

In each place of investigation, the firm, INSET, monitored the terrain subsidence in five points of which none of them monitored values of maximum subsidence directly above the collector's roof. In view of the fact that actual shape of the subsidence trough is analogical to Gauss curve, it is possible to use a regression analysis based on a Gauss curve shape regression function if we need to establish approximately the maximum value of soil settlement above the tunnel's roof, inflection point location, subsidence trough width and slope, all of which the calculations would be based on data of in situ performed measurements:

$$u(x) = u_{max}\ \exp^{\left(-\frac{x^2}{2 \cdot i^2}\right)} \qquad (2)$$

where:

u_{max} – Maximum value of settlement,

i – Location of inflection point.

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The subsidence trough slope, *d*(x), determined by the Gauss regression function, equals:

$$d(x) = u' = u_{\max}\left(\frac{-x}{i^2}\right)\exp^{\left(-\frac{x^2}{2.i^2}\right)} \quad (3)$$

The regression coefficients for subsidence troughs were determined taking into account all five points of each monitoring profile (Fig. 1) and utilising a statistic programme, UNISTAT,

The result of the regression analysis of the profile, PK 260 (Fig. 2) is a Gauss curve:

$$u(x) = 0.0445\ \exp^{\left(-\frac{x^2}{2\cdot 29.2}\right)} \quad (4)$$

Which means that $u_{\max}$= 0.0445 metres, inflexion point approximate location, i = 5.4 metres. The subsidence trough width, L, can be estimated by utilising the inflection point location. This is determined as a distance between two point of the Gauss curve, where the settlement values are not in excess of $u_{max}/8$, which in this particular case means 5.5 millimetres. The Gauss curve implies that the subsidence trough width, L = 2 x 2 x i = 21.6 metres.

The slope, d(x), is provided by the functional relation:

$$d(x) = -0.00152\cdot x\cdot \exp^{\left(-\frac{x^2}{2\cdot 29.2}\right)} \quad (5)$$

This particular subsidence trough is fairly wide; the limiting angle of influence is unrealistically low (about 42°) and it can be assumed that this subsidence trough results not only from the excavation of the sewer collector per se, but that the monitoring values imply also influences of realising a chamber next to the collector – see Figs. 5, 6.

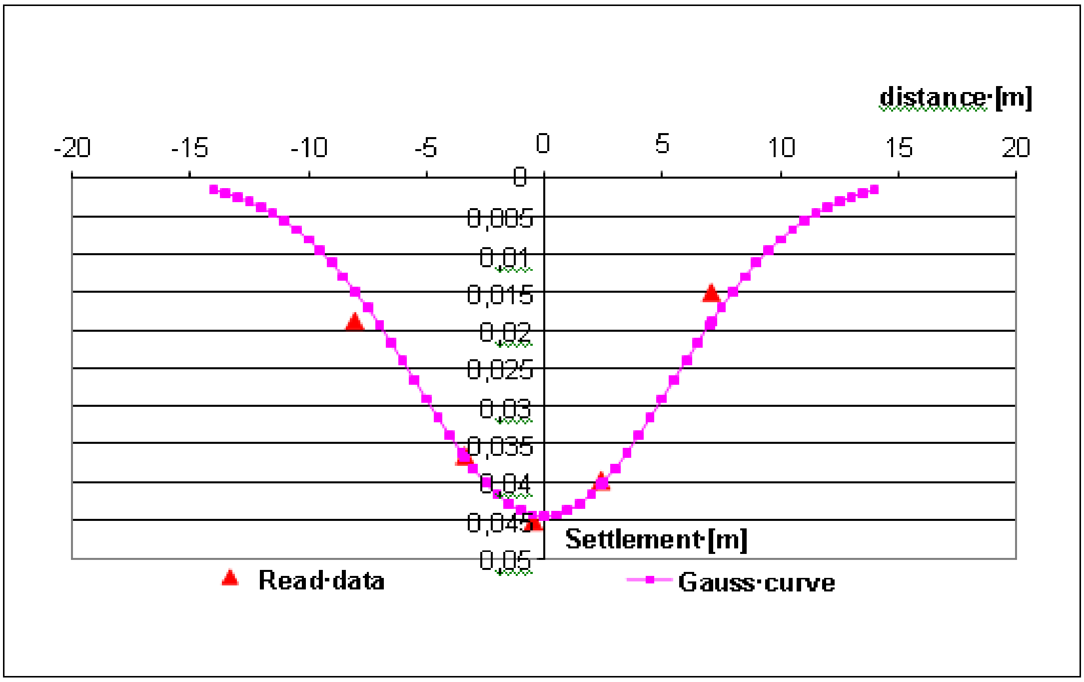

Fig.5 Gauss curve derived from Read data on points PK 260

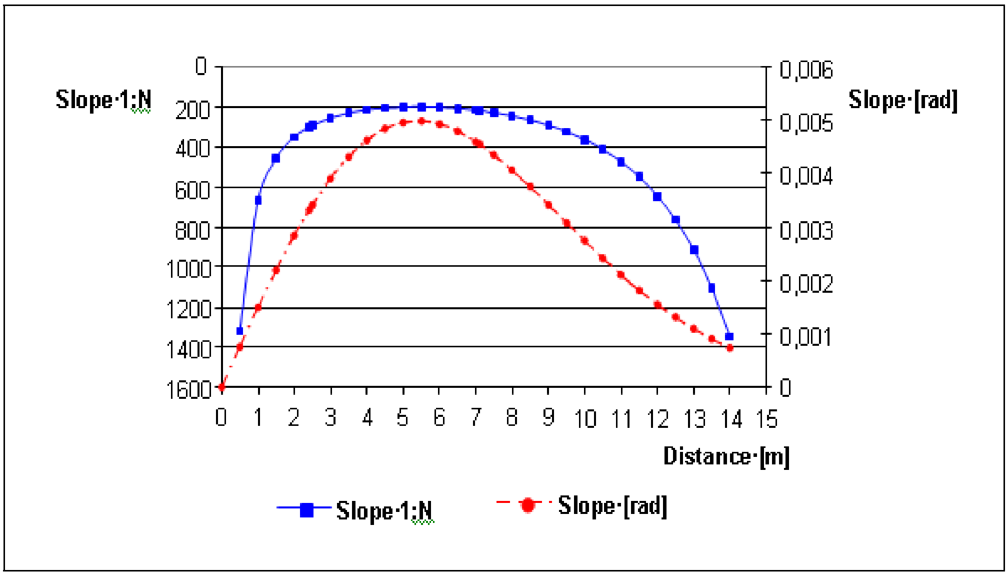

Fig.6 The slope of subsidence trough (Gauss curve) derived from Read data on points PK 260

Also the subsidence trough, PK 060, established by regression analysis, is analogically Gauss- shaped

$$u(x) = 0.0319\ \exp^{\left(-\frac{x^2}{2\times 11.09}\right)} \qquad (6)$$

Which means that u_{max}= 0.0319 metres, inflexion point approximate location, i = 3.33 metres. The subsidence trough width, L, can be estimated by utilising the inflection point location. This is determined as a distance between two points of the Gauss curve, where the settlement values are not in excess of $u_{max}/8$, that is approximately 4 millimetres, which results in L = 2 x 2 x i = 13.3 metres.

Again the slope, d(x), is provided by the functional relation:

$$d(x) = -0.00287 \cdot x \cdot \exp^{\left(-\frac{x^2}{2\cdot 11.09}\right)} \qquad (7)$$

The limiting angle of influence for this subsidence trough is 60 °, which corresponds with a commonly known expression of the limiting angle influence, 45°+φ/2 if the angle, φ = 31.5° , is valid for a stratum of sand and gravel.

The Gauss curve for the subsidence trough, PK 390, is provided by:

$$u(x) = 0.036\ \exp^{\left(-\frac{x^2}{2\times 29.98}\right)} \qquad (8)$$

i.e., u_{max}= 0.036 metres, inflexion point approximate location, i = 5.48 metres. The subsidence trough width, L, can be estimated by utilising the inflection point location. This is determined as a distance between two points of the Gauss curve, where the settlement values are not in excess of $u_{max}/8$, that is approximately 4.5 millimetres, which means that the width, *L* =2 x 2 x *i* = 21.92 metres.

The slope, *d*(x), is given by:

$$d(x) = -0.0012 \cdot x \cdot \exp^{\left(-\frac{x^2}{2\cdot 29.98}\right)} \qquad (9)$$

This subsidence trough is similar to PK 260 trough. It is wide enough, the limiting angle influence is only about 42 ° , and as such it is justifiable to claim that the subsidence trough is produced not only by the collector excavations but also by other factors if influence (for example due to excessive, unnecessary excavation).

4 SUBSIDENCE TROUGH CALCULATIONS BY AN IMPROVED METHOD OF NUMERICAL ANALYSIS

The following calculations for subsidence trough parameters were conducted by utilising an improved method of numerical analysis that has been developed by the authors of the paper [1].

In view of the fact that the method assumes a maximum of two geological strata, it was necessary to simplify the model. The model simplification is based on an assumption that soil layers above the collector's roof, i.e. backfill and sand-and-gravel represent decisive factors of influence concerning the subsidence trough quantitative and qualitative characteristics. Clay soils under the collector are not taken into account by computations. As such, the model assumes that the whole length of the collector is being excavated in a layer of sand and gravel and that it is overlaid by a backfill material.

As already noticed above, the calculations assume the collector to be of circular shape with radius of 2 metres. The influence of the actual U-shaped cross-section of the collector's face are accounted for by introduction of related shape coefficients, $koef_{tvarx}$ = 1.23, $koef_{tvary}$ = 1.32 [1], which are established by parameter numerical calculations. The effect of lining, which positively influences subsidence trough's origin, development, and character, was excluded by zero input of lining reaction. The calculations cannot account for ground water condition changes caused by the excavations.

In general, the calculation method consists of two steps:

1) Calculation of a partial subsidence trough at the boundary of the sand-gravel and backfill layers from the analytical calculation of a 'heavy semi-level', in which the excavated tunnel is located.
2) Calculation of the influence of this partial subsidence trough on the surface settlement. The Knothe's method was applied, for which the invariable of tunnelling influence and angle of tunnelling influence are characteristic. These Knothe's method determining parameters must be calibrated for each specific situation (tunnelling influence invariable, angle influence) [1].

The calculation results are in accordance with the note given above concerning large area of the subsidence trough, PK 260, which may be influenced by realization of a chamber close to the collector. The calculation, which only considered the influence of the collector itself, provides a subsidence trough of less extension with the inflection point value, i = 4 meters. The monitoring measurement values of actual settlement at points close to collector's vertical axis, B(262), B(263), B(264), are in fact identical with calculated ones. Differences between values of measurement and those of calculation are rather for points at greater distances, which especially concerns point, B(261) at the left side of the profile monitored. The maximum settlement value above the collector's roof, which was established by calculation, is 46.1 millimeters. The half of the calculated subsidence trough width is approximately 12 meters (a related value of settlement in marginal points is 0.6 millimeters). The maximum inflection point slope is provided by the ratio, 1:153. The results are illustrated by Fig. 7, 8.

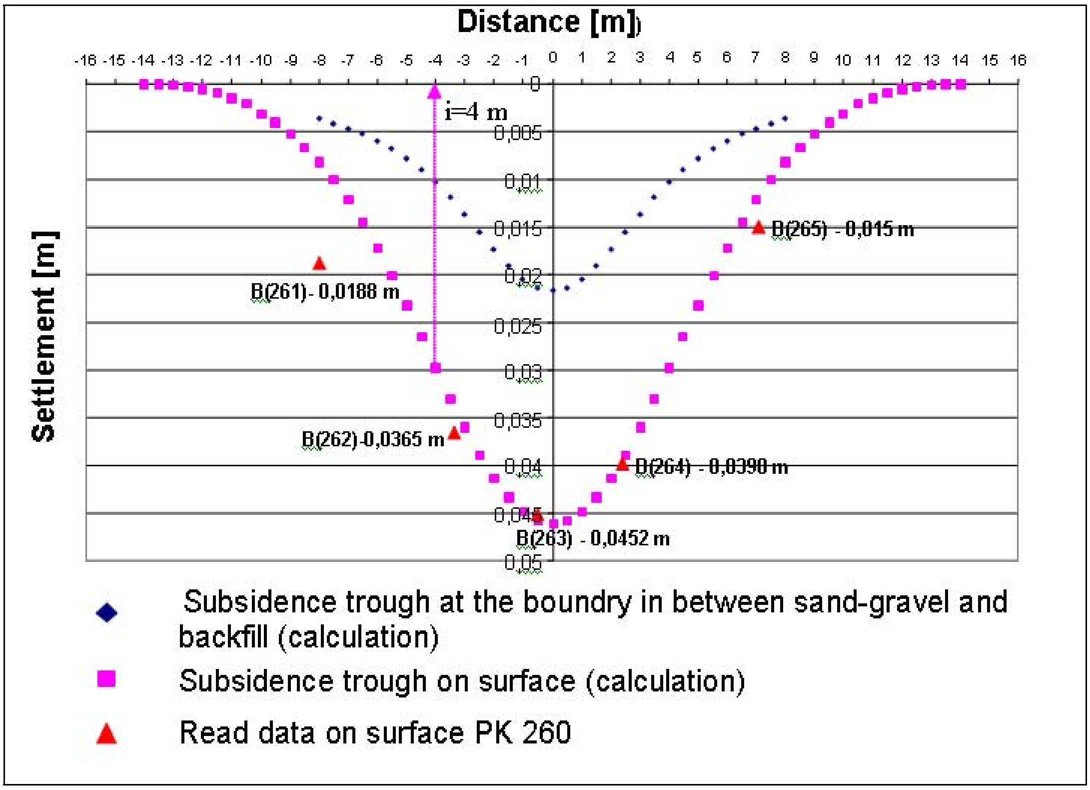

Fig. 7: Comparison of calculated and monitored values of settlement for PK 260

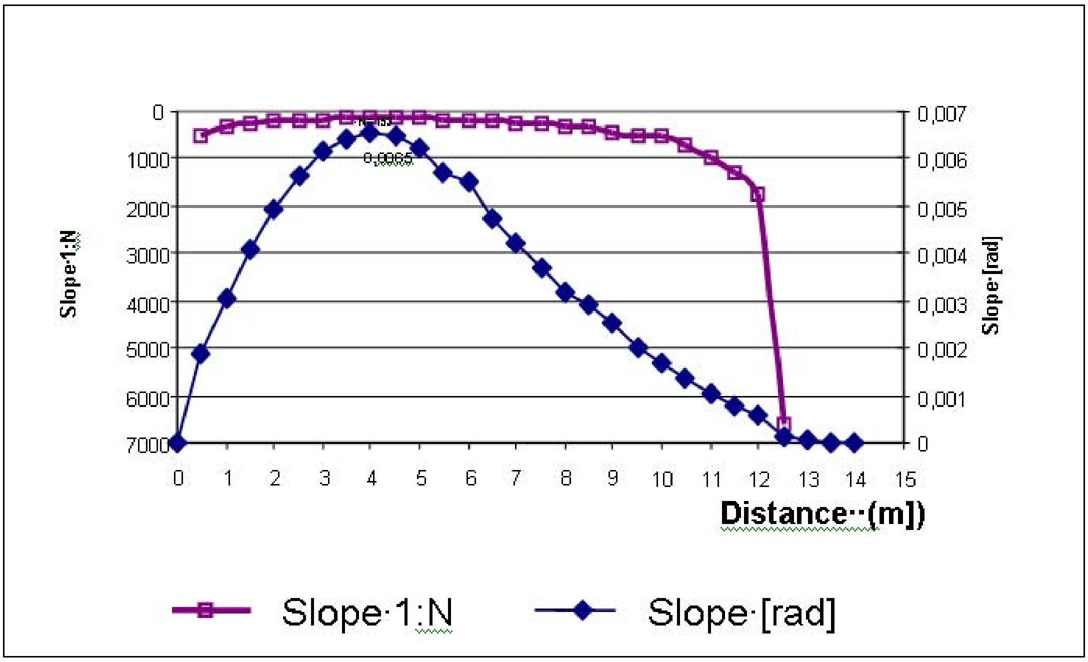

Fig. 8: Slope established by numerical analysis for PK 260

The same method was applied also for profiles, PK 060 and PK 390.

5 EMPIRICAL APPROACH TO ESTABLISHING OF SUBSIDENCE TROUGH PARAMETERS

Empirical approaches to definition of subsidence trough parameters are based on knowledge of measurement data of actual settlement events. Most of these measurements are in accordance with the Gauss function, as regards their fault distribution curve. All empirical methods for establishing of settlement curves are based on the Gauss function. The medium characteristics (compact or loose soil, loose soil under groundwater level), extension and location of actual tunneling (tunnel radius and its depth of location under surface; and ground loss of excessive excavation) [5] determine the subsidence trough and are implied in the parameters of the Gauss curve.

Two parameters are decisive for defining of the subsidence trough curve. The first of these is the inflection point distance value from the centre of the tunnel (i). The other is represented by the value of maximum settlement above the tunnel's centre (u_{max}).

The inflection point value (i) defines width – extension of the subsidence trough. It depends on the medium, and also parameters of tunnelling – depth of the tunnel location under surface (*H*) and tunnel radius (*R*) – influence the subsidence trough extension.

The value of the maximum settlement above the tunnel's centre (u_{max}) depends on the ground loss (V_0). The ground loss is an outcome of technology and methods used for realisation of the tunnel. It is also subject of human factor and actual conditions of realisation, which are difficult to predict and quantify.

The maximum settlement value above the tunnel's centre (u_{max}) is determined by the condition of identity of the ground loss plane (V_0) and subsidence trough (the Gauss curve integral value). The approximate calculation of the maximum settlement (u_{max}) is provided by [5]:

$$u_{max} = V_0/(2{,}5\ .\ i) \qquad (10)$$

The inflection point distance value is of decisive influence for shaping of subsidence troughs. Its magnitude is derived from experience with actual tunnelling excavations if empirical methods are concerned (see Fig. 9).

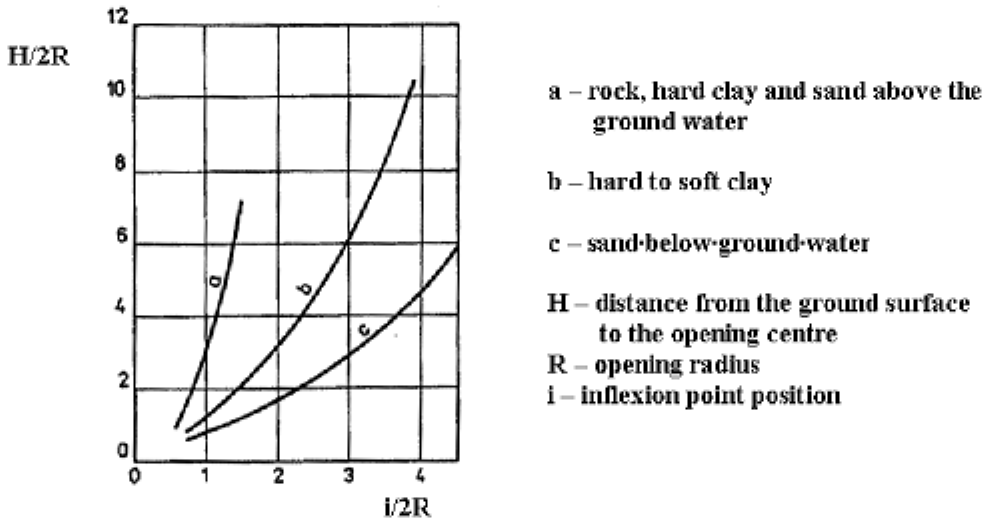

Fig. 9 Dependency of subsidence trough characteristics on ground conditions (Peck, 1969)

The inflection point distance measurements (Fig. 9) are fundamental for determining of analytical relations that enable establishment of the distance.

A polynomial function, which provides for determination of relations presented by Fig. 9, is:

$$i/R = (H/2R)^n \quad (11)$$

The exponent (n) can have different values: n = 1.0 (Attewell, 1977); n = 0.8 viz. [4]. The inflection point distance depends on R (tunnel radius) and H (depth of tunnel location under suface). The exponent (n) is the same for all medium types. The exponent constant value results in a single curve that equalizes the medium influence on the subsidence trough development.

A function choice can provide for a better accounting for the medium characteristics. Such function must enable expression of a system of curves of which each would represent a specific type of medium. An exponential function can provide for the purpose:

$$i = k_1 \,.\, R \,.\, exp^{[k_2 \cdot \ln(H/2R)]} \quad (12)$$

Where:

(k_1), (k_2) - Specific medium (soil) coefficients (according to curves a, b, c; Fig. 8)

Tab. 2: Coefficient values, k_1 and k_2, derived from relations of Fig. 8 (Peck, 1969)

Medium type	k_1	k_2
Consistent clay, sand above ground water	0,5912	0,4646
Soft clay	0,9009	0,6491
Sand above ground water	1,2899	0,7207

The establishment of the ground loss parameter (V_0) can be, for example, based on monitoring the mass of soil excavated per one meter of tunnelling or by convergence evaluation. It is not conducted in practice. This parameter is just a matter for qualified estimation. It depends on the tunnel size and medium of excavation and its range is between 2 and 6 % of the projected tunnel face, where the lower range values signify a better technology of excavation used for realisation of the tunnel.

If we know the actual values of settlement, we can - by varying the ground loss parameter (V_0) - adapt the actual subsidence function to actual conditions, i.e., we can make the values of the exponent, *n,* or coefficients, k_1 and k_2, more accurate. At least, three actual settlement values are needed that would be located on one arm – slope of the subsidence trough. The first of these should be localized above the tunnel, best on its vertical axis. This value is important for better accuracy of the ground loss parameter (V_0). The other two points of measurement should be at sides of the assumed inflection point. Values of these two points are important for tuning of the subsidence curve course, i.e. for establishment of the coefficient *(n),* or (k_1) and (k_2).

The following Figs. 10 and 11 illustrate the subsidence trough curves above the collector roof, profile, PK 060. The substitute radius of the collector is 2 metres and its centre is located 8 metres under surface. Analogical outputs were also provided for profile situations, PK 260 and PK 390.

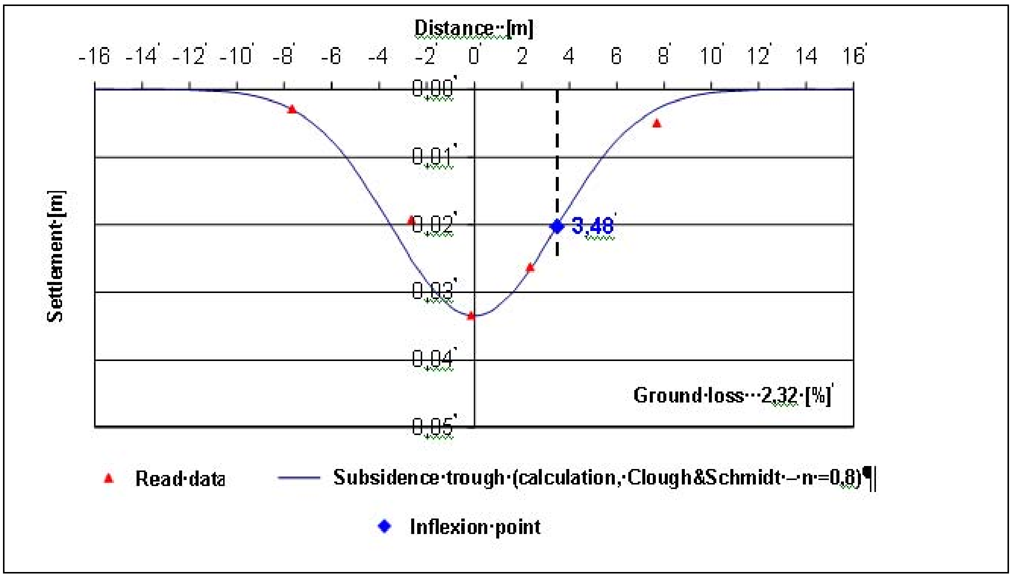

Fig.10

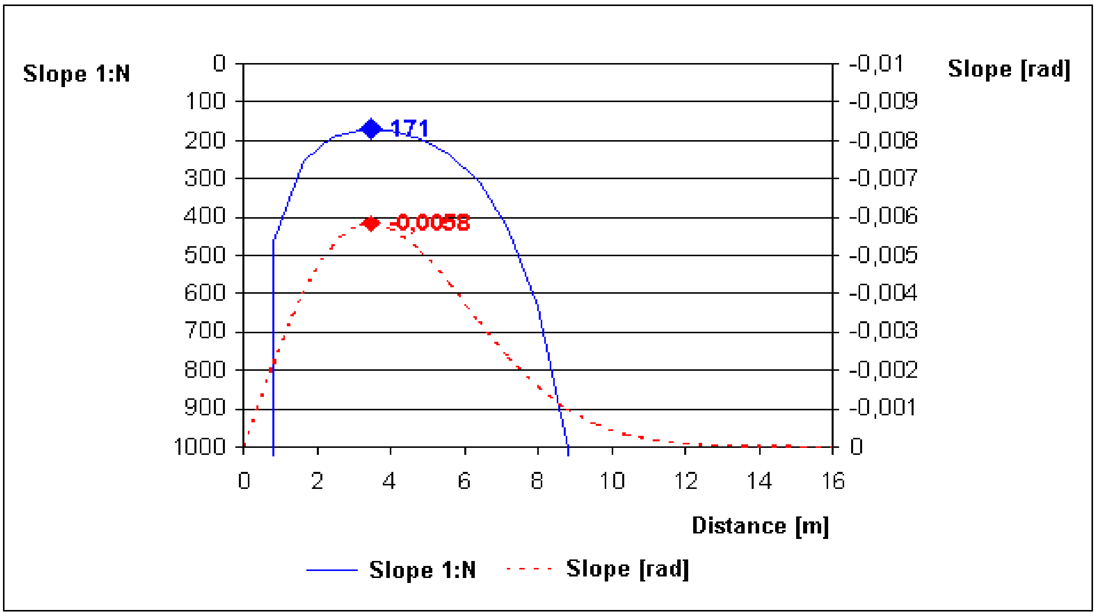

Fig. 11

6 SUMMARY FOR EMPIRICAL APPROACHES TO PREDICTION OF SHALLOW EXCAVATION SUBSIDENCE TROUGHS

Comparing results of actual subsidence trough measurements with calculations based on the Gauss function, it can be concluded that this function is suitable for analytical expressions of subsidence trough curves. The Gauss function parameters imply basic facts of medium characteristics, tunnel size values, technology and method of excavation realization.

The value of the inflection point horizontal distance from the centre of the tunnel is of major importance as regards the subsidence trough shape. A tentative estimation of this distance can be based on commonly acknowledged hypotheses and methods derived from them [3], [4], [5]. The graphics of the calculated subsidence curve and to it related actual measurement values attest to consistency between calculated and measurement data of settlement.

Two different relations can be used for calculating the inflection point distance. The relation (11) works with a single parameter, the relation (12) works with two parameters. They enable implication of the medium characteristic in the inflexion point calculation. The relation (11) modifies the exponent, n; the relation (12) modifies two coefficients, k_1 and k_2. The analysis cannot specify which of these relations is better suited for the purpose of calculating the inflection point distance.

This method can provide for prognostication of subsidence trough slopes. An improvement of the method prediction value is conditioned by a deduction of related parameters

7. FINAL COMPARISON OF MODEL GENERATED AND ACTUAL SUBSIDENCE TROUGHS

Concerning an example of the profile, PK 060, Fig. 12 illustrates results of comparing settlement values acquired by empirical methods with those generated by an improved method of numerical analysis.

It is obvious that empirical results are very close to those produced by the improved method of numerical analysis as regards settlement values of the profiles, B(062), B(063) and B(064), in close vicinity to the collector's vertical axis. The measurement points, B(061) and B(065), are located on subsidence trough edges, and differences between calculated and empirical data are more pronounced (if only approximately 5 millimetres at the right side of the subsidence trough). Only the method of Clough&Schmidt (n = 0,8) provides for a better consistency even in this subsidence trough boundary area.

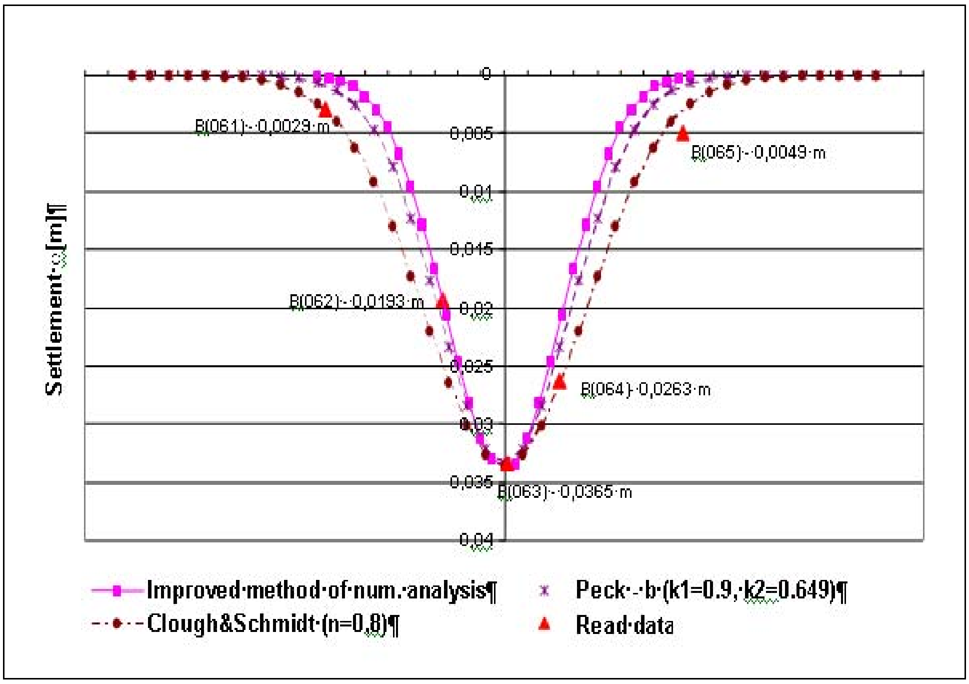

Fig. 12: Comparison of empirical and calculated settlement parameters for the profile, PK 060

The maximum settlement value, 33 millimetres, is the same for all three calculation methods. The inflection point distances from the vertical axis rather vary, as it is given by Tab. 3.

The bottom boxes of the Tab. 3 provide for subsidence trough characteristics that have been acquired by simple superimposing of the Gauss curve and the values of actual measurements.

Tab. 3: Calculated characteristics of the subsidence trough, PK 060

Method	Volume loss [%]	Maximum settlement calculated [m]	Inflection [m]	Maximum inflection point slope	Maximum relative horizontal deformation *)
Peck curve b (K1=0,9; K2=0,649)	1,88	0,0334	2,83	1:139	0,004
Clough&Schmidt (n=8)	2,32	0,0335	3,48	1:171	0,0035
Improved method of numerical analysis	-	0,0337	2,5	1:124	0,005
Regression from measurement values (Gauss curve)	-	0,0319	3,33	1:179	0,003
*) Maximum relative horizontal deformation has been approximated by: ε_{max} = 0.6 slope multiple in inflection point (Bradáč)					

8 CONCLUSION

Comparing empirical and model generated data, it can be concluded that calculation are of practical applicability. Nevertheless, empirical methods of calculations ask for consistent calibration of the calculation model due to empirical coefficients used by the calculation. If this is the case, the Knothe method needs appropriate choice of two already mentioned parameters, namely the invariable and the angle of tunnelling effects.

Another outcome of the comparison performed is in the fact that better agreement calculated and measurement data of settlement is in area close to tunnel vertical axis. In general, calculated values of the subsidence trough width are less of those provided by actual measurements. This difference can be caused by other factors of settlement at subsidence trough boundary areas. These factors (influence of nearby excavation, influence of ground water level variations due to progress of excavation, influence of ground loss) could not provide for inputs of calculations. Flexibility and relative applicability easiness are advantages of calculation methods. They do not need a lot of input data, modelling is easy and fast, and calculation times are very short, usually just a few seconds. Accounting for other factors of settlement would ask for utilisation of numerical methods of modelling (for example finite element method) that is much more demanding both from the point of view of input data requirements and calculation times needed.

Recommendations

The analyses and comparisons of actual measurement and calculated subsidence trough data have demonstrated that:

→ For purposes of preliminary subsidence trough prognosis, the loss of ground method seems to be the best option if empirical coefficients, ΔV = approx. 2-3%; k_1, k_2, are used. These empirical coefficients can be established with such accuracy that the subsidence trough prognosticated data can also serve purposes of building construction planning, design and realisation.

→ The improved method of numerical analysis and finite element methods should be applied in difficult geotechnical conditions. The prediction accuracy of these methods is high with only 3-5% variations. The finite element modelling can incorporate other geotechnical and geological factors, increasing the prediction accuracy further.

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