Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)
© 2019 Taylor & Francis Group, London, ISBN 978-1-138-38865-9

Correlation approach between surface settlement and TBM pressure parameters

V.H. Franco
Universidade de Brasília, Brasília, Brazil

H.C. Rocha
Companhia do Metropolitano de São Paulo, São Paulo, Brazil

A.A.N. Dantas, T.A. Mendes & A.P. Assis
Universidade de Brasília, Brasília, Brazil

ABSTRACT: TBMs have become an excellent tool for a fastest development of the underground space in urban areas. An important aspect of its operation, either by EPB or slurry, is the control of the tunnel face stability aiming to minimize the effects on the surrounding ground both during boring and standstill. Moreover, a continuous monitoring campaign is mandatory to check if the assumed risks stand inside the limits of integrity on the nearby buildings. Hereupon, the need for a relation between the TBM face support pressure and the immediate surface settlement has become a matter of interest. Therefore, the following paper is presented with the goal to provide a correlation approach to relate these two important features of tunneling. To achieve that, data from the extension works of São Paulo metro Line 5 will be used to frame the basis of the correlation approach here proposed and proved to fit well.

1 INTRODUCTION

Undoubtedly, nowadays, the use of tunnel boring machines (TBMs) has played an important role in the increase of underground infrastructures. Long distance covering, fastest construction cycle per tunnel section, control of construction (e.g. excavated material, face stability, concrete lining quantity), safe work environment and the relative low impact on inducing of ground movements have been the reasons behind its success over conventional tunneling methods in the urban areas.

The use of either earth pressure balance (EPB) or slurry shield (SS) machines will depend particularly on the type of soil to be excavated and the presence of groundwater level above tunnel if any. Even though, Maidl et al. (2012) indicated that the range of application of EPB machines can be extended far into the area of application of SS machines by the addition of some chemical agents, to the muck in the excavation chamber.

Regarding tunneling effects, it is well known that the construction of tunnels, in an urban environment, inevitably induces ground movements, which according to Leca et al. (2007) is a consequence of the rupture of the ground mass stability that begins at the tunnel face and propagates to the surface in the form of settlements. For the case of TBMs, the stability of the tunnel face is achieved by the continuous application of support pressure from the excavation chamber. A detailed explanation on the mechanism functioning for applying support pressure, either on EPB or SS machines, as well as its theoretical estimation is provided by Guglielmetti et al. (2008) and Maidl et al. (2012).

On the other hand, the firsts to represent the settlements at surface were Peck (1969) and later Attewell and Woodman (1982) which considered the shape of surface deformation as a settlement trough. These authors used an empirical approach to study this. However, there exist others approaches that can be employed like analytical solution (Loganathan and Poulos, 1998), numerical approaches (Rowe et al., 1983; Lee and Rowe, 1990) and modeling test (Atkinson and Potts, 1977; Mair and Taylor, 1997).

In general, at the design stage and during tunnel construction, it is of common practice to analyze the surface settlement and the tunnel face stability separately. Therefore, arises the interest

Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)
© 2019 Taylor & Francis Group, London, ISBN 978-1-138-38865-9

by the authors to inquire about this topic. In this contest, some references about correlation of these two important variables can be mentioned as: Macklin (1999) which, based on the concept of a Load Factor (*LF*) proposed by Kimura and Mair (1981) from results of geotechnical centrifuge tests, proposed a relationship to estimate the volume loss; Repetto et al. (2006), where through back analyses of the EPB performance used for the construction of a 7 km railway tunnel below the city of Bologna – Italy, presented a diagram to correlate the face support pressure with volume loss and, lastly, Fargnoli et al. (2013) which, by studying the case of the new Milan underground line 5, attempted to relate the surface settlement with the face pressure.

Thus, by considering the statements indicated above as well as the reviewed attempts, the present paper is intended to provide a correlation approach for estimation, during TBM tunneling, of surface settlement in relation to support face pressure. The aim of this approach is to provide an additional tool to evaluate ground movement due to mechanized tunneling in urban dense areas, where its estimation is paramount.

Considering the importance of framing the proposed approach to a case study, information regarding surface settlement monitoring campaign and support pressure data of an EPB machine for the extension works of Line 5 of the São Paulo metro system will be used.

2 PROJECT BACKGROUND

The tunnel project regards 11.5 km of extension works of São Paulo metro Line 5 in the highly dense south region of the city of São Paulo – Brazil (Figure 1). The extension works of the line involve the construction of eleven stations, thirteen ventilations and emergency exit shafts, one parking station and one depot “Pátio Guido Calói”.

The construction of the 11.5 km extension line was divided in: *i*) 0.63 km excavated by the sequential method; *ii*) 5.13 km excavated by Ø 6.9 m diameter EPB machine (two single track tunnels) and *iii*) 5.74 km excavated by Ø 10.6 m diameter EPB machine (double track tunnel).

In a specific way, the following work deals with information regarding the excavation of the double track tunnel stretch between the ventilation and emergency exit shaft of Bandeirantes and Dionísio Da Costa (points A and B respectively from Figure 1). The intense instrumentation campaign carried out along the stretch line, the relative simplicity of using one EPB machine for the same stretch, the almost regular disposition of soil layers and the fact that was a reuse TBM machine with the same working crew were the reasons for selecting this part of the line to implement the propose approach.

Figure 1. Layout of extension works of São Paulo metro Line 5. Case study area between Hospital São Paulo and Santa Cruz station (top right corner).

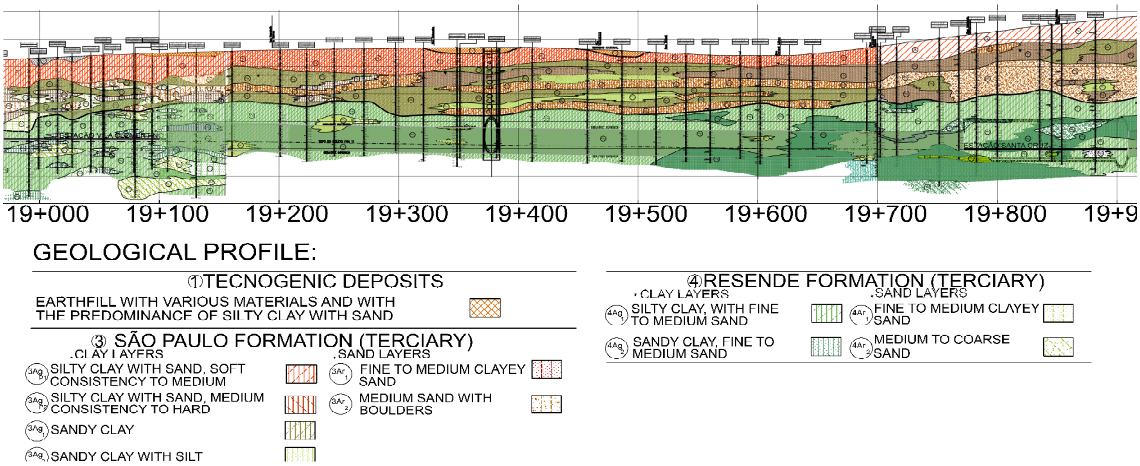

Figure 2. Geological profile between Hospital São Paulo and Santa Cruz stations (HSP – SCR).

2.1 *Geological and geotechnical features*

Briefly speaking, the ground around the tunnel stretch is formed by the São Paulo formation which consists in sediments of red porous silty clays, silty-sandy clays and clayey sands, and the Resende formation formed by sediments of gray and yellow silty clays and yellow and orange silty-clayey sands. The major part of the tunnel excavation goes through the transition zone between these two formations. Figure 2 shows the geological profile between Hospital São Paulo and Santa Cruz stations. Besides, Table 1 summarizes the main geotechnical parameters of the soils presented along the tunnel stretch.

Table 1. Geotechnical parameters of groundmass presented along tunnel stretch.

Geotechnical Parameters		**3Agp$_1$***	**3Ag$_{1,2}$***	**3Ar$_{1,2}$***	**4Ag$_{1,2}$***	**4Ar$_{1,2}$***
γ	kN/m³	16.6	18.5	19.5	20.2	19.6
k$_0$	-	0.67	0.88	0.77	0.71	0.83
c	kPa	18	40	7	80	4
φ	º	24	24	32	26	32
E$_0$	MPa	20	120	185	230	162
ν	-	0.26	0.30	0.31	0.28	0.28

* Geological units are indicated in Figure 2.

2.2 *TBM face pressure and monitoring data*

The TBM used for the extension of Line 5 is characterized to have 335 machine parameters (electronic sensors) that allow TBM operator and technicians to perform tunnel excavation in terms of guidance, excavation process, hydraulic and lubrication of mechanical parts as well as health and safety warnings.

From all the TBM sensors, the face support pressure and grout injection pressure constitute the main TBM components for the achievement of ground stability during tunneling (Guglielmetti et al., 2008; Maidl et al., 2012 and Mollon et al., 2012). In this study the focus of implementation of TBM support pressure regards mainly the face support pressure. Figure 3 shows the allocation of the seven earth pressure balance sensors.

All along the tunnel stretch, a number of 2977 rings were installed. Thus, information about face support pressure during excavation for installation of these rings were available. Table 2 shows a summary of best fitted probability distribution function (PDF) for every pressure sensor of the TBM registered during tunneling. The values of coefficient of variation (CV) in this table help to illustrate the effects of variability. With CV < 20 % implies major control on applying face support pressure.

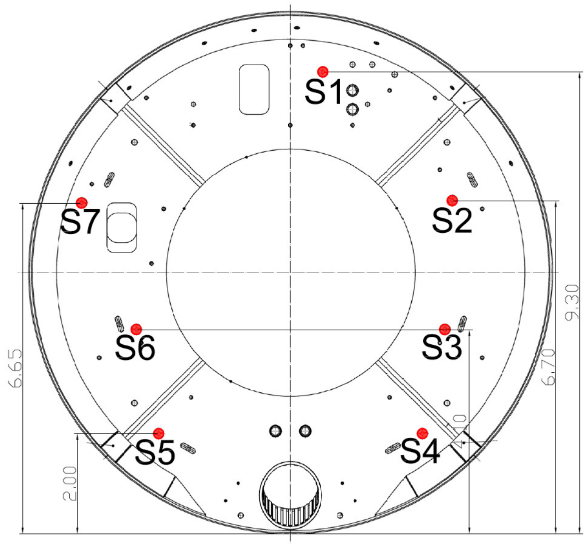

Figure 3. Allocation of TBM face support pressure sensors.

Table 2. Summary of best fitted PDF for face support pressure along the tunnel stretch.

TBM Sensors	PDF	Parameters Max. Likelihood	Mean (kPa)	Std Dev (kPa)	CV (%)
EPB - S1	Lognormal	μ = 5.22225 σ = 0.195442	188.294	37.212	20
EPB - S2	Weibull	α = 7.15073 β = 231.885	217.153	35.771	16
EPB - S3	Normal	μ = 250.92 σ = 30.8159	250.92	30.816	12
EPB - S4	Lognormal	μ = 5.63268 σ = 0.154504	282.766	43.951	16
EPB - S5	Gamma	*a (Shape)* = 38.0527 *b (Scale)* = 7.2786	276.973	44.899	16
EPB - S6	Normal	μ = 248.152 σ = 31.4733	248.152	31.473	13
EPB - S7	Weibull	α = 7.22592 β = 230.101	215.598	35.172	16

Regarding monitoring data, a total of 92 surface monitoring sections were analyzed. The transverse settlement trough from the measurements were used for the analysis. In this manner, Table 3 shows a summary of the maximum surface settlements. The length of the tunnel stretch (5.74 km) was splitted in seven zones. These zones were delimited between launching and arriving TBM structures (i.e.: Shaft and Stations), in order to have areas with homogenized ground behavior.

Table 3. Summary of estimation of settlement curve parameters according to Peck (1969).

Zone	Sections	*Smax (mm)*		
		μ	σ	*CV (%)*
BAN – EUC	4	5.33	1.873	35
EUC – MOE	16	2.40	1.219	51
MOE – SER	24	3.00	2.654	88
SER – HSP	12	2.01	1.057	53
HSP – SCR	**19**	**2.69**	**1.246**	**46**
SCR – CKB	10	3.90	4.226	108
CKB – DDC	7	5.55	9.293	168

Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)

From the information shown in Table 3, it is possible to conclude that the zone between Hospital São Paulo (HSP) and Santa Cruz (SCR) stations provided a better result in terms of CV, which could be interpreted, from the statistical point of view, as a zone with a better homogenized behavior respect to the other tunnel zones.

3 CORRELATION APPROACH

3.1 *Proposed equation*

The model presented by Atkinson (2007) shows that, during TBM tunneling, as the applied support pressure decreases the volume loss increases. Furthermore, when the support pressure is the same of the vertical stress, at the axis level, the volume loss will be negligible, and as well as the support pressure reaches the ground ultimate limit state the settlements will become very large up to its collapse.

In order to be able to represent mathematically this consistent behavior of ground movement due to TBM support pressure, the hyperbolic equation implemented by Duncan and Chang (1970), to describe nonlinear analysis of stress – strain behavior of soils, was taken as reference. So, by adapting this formulation to the model presented by Atkinson (2007), the following equation is proposed:

$$S_{\max} = \frac{(P_0 - P)}{a - bP} \tag{1}$$

where S_{max} = maximum surface settlement (mm), P = applied TBM support pressure (kPa), P_0 = estimated initial TBM support pressure for face stability, and a and b are curve-fitting parameters (the physical meaning of these variables are not subject of discussion in the present work).

Figure 4 shows the representation of the proposed mathematical formulation (from Eq. 1) to express the nonlinearity behavior of ground due to the applied TBM support pressure. This equation represents a good mathematical approach to reproduce model presented by Atkinson (2007). If the applied TBM support pressure equals the initial stress of the soil (P_0), thus the settlement at surface will be negligible.

By reducing the applied support pressure (P) is observed that the soil deformation follows an elastic behavior. After that the limit is reached and then the development of soil plastic behavior begins to be noticed, meaning in large surface settlement which won't be more recoverable. Large settlement and ,consequently, tunnel face collapse is achieved when the applied TBM support pressure reaches a minimum value (P_{min}).

The slope of the proposed curve is obtained through the following mathematical derivation:

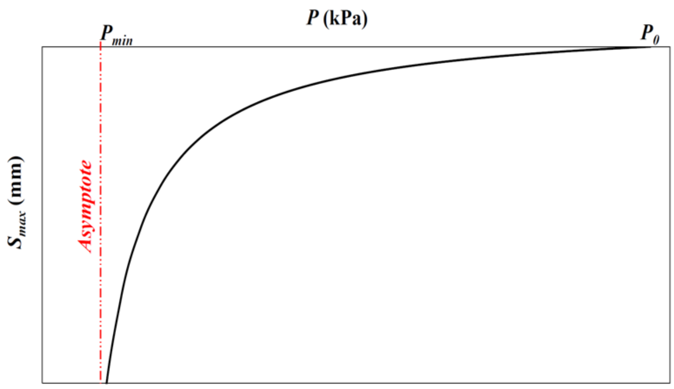

Figure 4. Representation of the proposed Immediate Surface Settlement Curve (ISSC).

$$\left.\frac{dS_{\max}}{dP}\right|_{P\to P_0} = -\frac{1}{a-bP_0} \tag{2}$$

The value of minimum applied pressure (P_{min}) to have the maximum surface settlement (S_{max}) is mathematically demonstrated by first transforming P (from Equation 1) as a function of the maximum surface settlement (S_{max}), which is:

$$P = \frac{P_0 - aS_{\max}}{1-bS_{\max}} \tag{3}$$

Therefore, as S_{max} approaches infinity the value of P_{min} in which large settlement and/or tunnel face collapse will be achieved by the following expression:

$$\lim_{S_{\max}\to\infty}\frac{P_0 - aS_{\max}}{1-bS_{\max}} = P_{\min} = \frac{a}{b} \tag{4}$$

3.2 *Parametric analysis of the proposed equation*

In order to analyze the impact of the fitting-curve parameters, presented in the proposed equation, a series of parametric analyses are made to describe this influence. As shown in equation 1, the fixed input variable is the initial TBM face support pressure (P_0), which value depends on the case study under analysis.

In this regard, by considering the monitoring data analysis shown in Table 3, the tunnel stretch between Hospital São Paulo (HSP) and Santa Cruz (SCR) stations was chosen as reference to extract the information required to perform this analysis. Thus, the analytical method proposed by Anagnostou and Kovari (1996), based on limit equilibrium method, was implemented for the estimation of face support pressure.

Figure 5 shows the model geometry for estimation of the face support pressure (P_0), by considering the geological profile between HSP – SCR stations as shown in Figure 2.

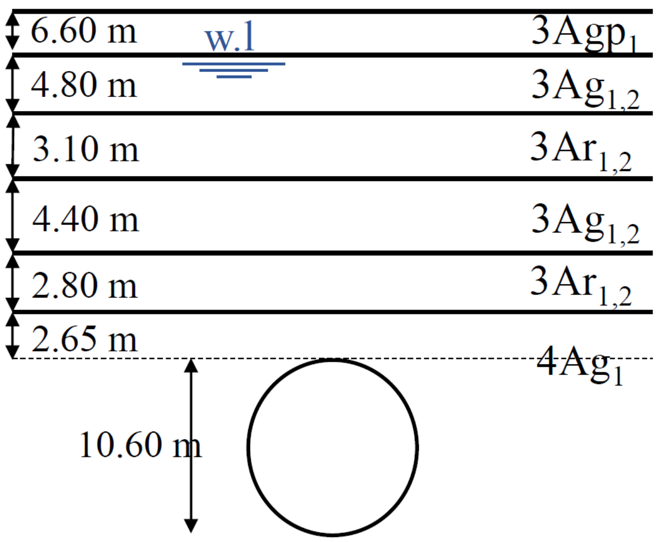

Figure 5. Tunnel model geometry between HSP – SCR stations.

Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)
© 2019 Taylor & Francis Group, London, ISBN 978-1-138-38865-9

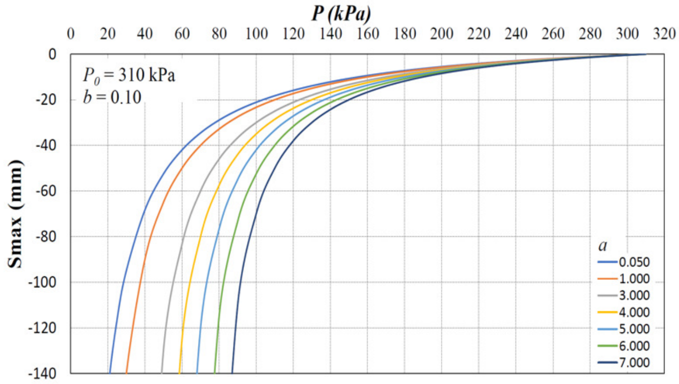

Figure 6. Effect of changing *a* on ISSC.

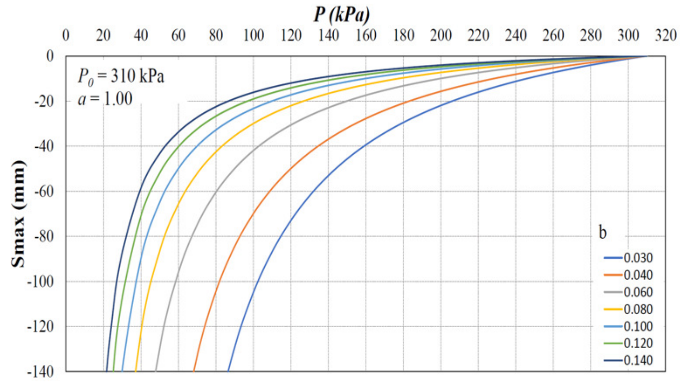

Figure 7. Effect of changing *b* on ISSC.

Therefore, by implementing the method of Anagnostou and Kovari, the estimated value of face support pressure was 310 kPa. Figures 6 and 7 shown the effects of variation the fittig-curve parameters. By analogy with the Duncan and Chang formulation's, *a* constitutes the slope of the curve indicating a linear behavior and *b* correspond to the asymptotic tendency of the curve is achieved when the applied face support pressure is minimum (P_{min}), thus the surface settlement tends to be large or infinite (tunnel face collapse).

3.3 *Fitting the proposed equation to case study monitoring data*

Measured surface settlements monitoring data, along the tunnel stretch between HSP – SCR stations, were selected to show the fitting suitability of the proposed equation. As it well known, within the mathematical literature, the coefficient of determination of R-squared is an inadequate measure for the goodness of fit to apply directly in nonlinear models. Nevertheless, it is still a frequently tool use for the analysis and interpretation of nonlinear fitting to data.

An example, to the mentioned above, is given by Spiess and Neumeyer (2010) which performed thousands of simulations for their study on pharmacology and got to the conclusion that the use of R-squared to evaluate the fit of nonlinear models leads to an incorrect interpretation.

Under this context and by taking it to the present scenario, firstly a mathematical artifice was applied to linearized the propose equation and on this linear equation, the goodness of fit analysis was applied by using the minimization solver available in MS *Excel 2016*.

Figure 8 presents the best-fit curve to the observed data, the value of R-squared presented correspond to that applied to the equivalent linear equation model which by relation can be considered the same for the proposed model. The value of fitting parameters *a* and *b* obtained were 9.850 and 0.211, respectively.

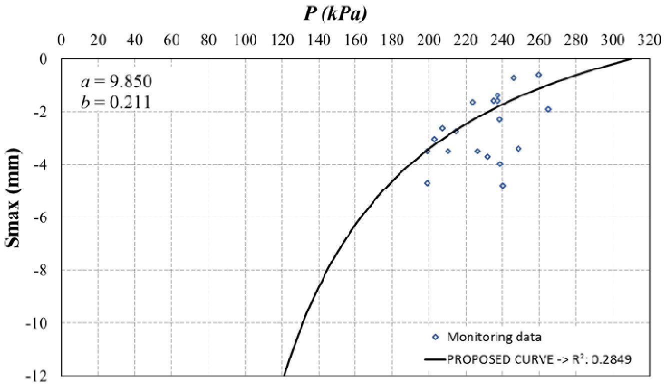

Figure 8. Best-fit curve to the monitoring data along the tunnel stretch between HSP – SCR stations.

3.4 *Quantification of variability to the proposed equation*

The following analysis is based on the work of Zhai and Rahardjo (2013), which procedure applied for the understanding of the Soil Water Characteristic Curve (SWCC), that can be perfectly taken to apply to this case.

The idea of this procedure will be to represent the upper and lower bounds of the proposed equation (Equation 1). According Kool and Parker (1988), The bounds of a model is directly correlated to the confidence limits of the parameters involved in the equation. This can be done by estimating the variance of each parameter by approximately using t-statistic as follows:

$$\begin{aligned} a &\sim [a_{\min}, a_{\max}] = \left[a - t_{\alpha/2}\sqrt{\text{var}(a)}, a + t_{\alpha/2}\sqrt{\text{var}(a)}\right] \\ b &\sim [b_{\min}, b_{\max}] = \left[b - t_{\alpha/2}\sqrt{\text{var}(b)}, b + t_{\alpha/2}\sqrt{\text{var}(b)}\right] \end{aligned} \quad (5)$$

where α is the confidence level (95%). Thus, by the combination of the maximum and minimum values of the fitting parameters on the proposed equation, the upper and lower confidence limits can be obtained.

Figure 9 shows the correlation between the maximum surface settlement with fitting parameters *a* and *b*, respectively.

Therefore, the combination of a_{max} and b_{min} will give the upper bound while the combination of a_{min} and b_{max} will give the lower confidence limit. The confidence limits are expressed as follow:

$$\begin{aligned} Upper: S_{\max} &= \frac{P_0 - P}{a_{\max} - b_{\min} P} \\ Lower: S_{\max} &= \frac{P_0 - P}{a_{\min} - b_{\max} P} \end{aligned} \quad (6)$$

Finally, Figure 10 shows the variability of the proposed equation through computation of the upper and lower confidence limits. In order to be able to compute this procedure it was assumed a coefficient of variation (*CV*) of 20% for both the fitting parameters, which will allow to estimate the variance, and a $t_{\alpha/2}$ = 2.093 (α=95% with n = 19 observed data assumed, from Table 3, as the degree of freedom).

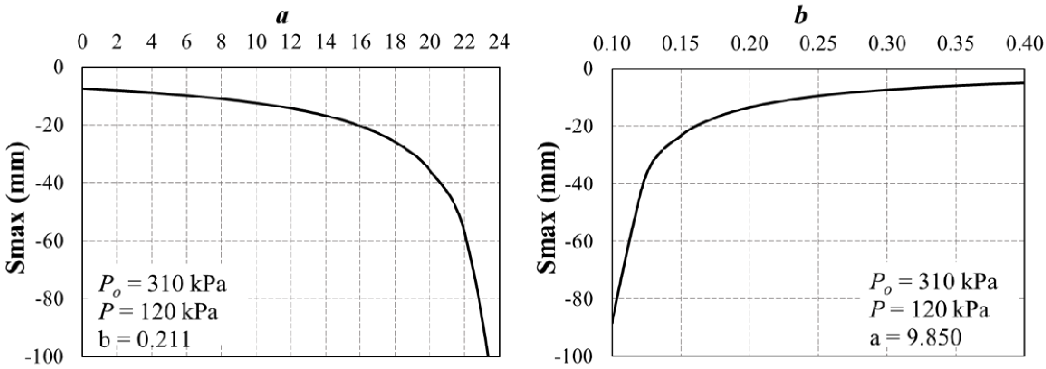

Figure 9. Relationships between maximum surface settlement (S_{max}) and fitting parameters a and b, respectively.

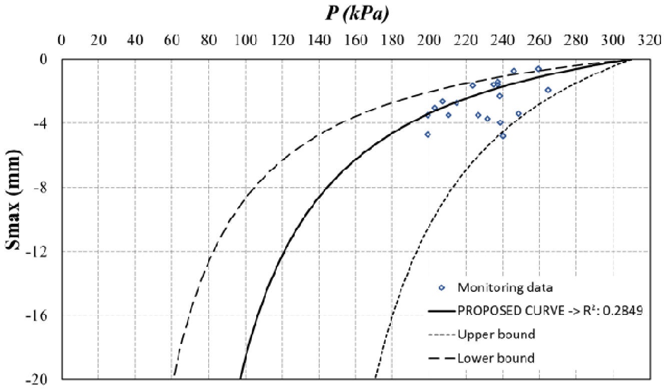

Figure 10. Illustration of the best fitted, upper and lower bound limits of maximum surface settlement between HSP – SCR stations.

4 CONCLUSIONS

The present paper was intended to show a proposed equation for relating the applied TBM face support pressure with the immediate surface settlement, which is credited to be of helpful for the personnel involved during tunnel construction with TBMs in urban areas. This formulation is based in the hyperbolic equation that provided an excellent result to the nonlinear constitutive model proposed by Duncan and Chang (1970) and proved to be an excellent tool to relate these variables.

A rationale procedure for the estimation of the fitting parameters was presented on the basis of having information regarding TBM support pressure and field monitoring data. To this case, it was taken data from the extension works of São Paulo metro Line 5. Thus, the values of fitting parameters a and b regarded only to the tunnel stretch that was studied. The analysis, with the proposed equations and upper and lower confidence limits, have shown that excavation proceeded inside the expected range of correlation. The approach here implemented to this case study can be applied to other tunneling projects.

The explanation of the physical meaning of the fitting parameters was not the subject of discussion in the present work.

For other TBM tunneling projects, the proposed equation could be used by considering the local characteristics where tunnel will be constructed, which is an important aspect because allow to estimate, for example, the initial support pressure (P_0) which intrinsically considers variables as tunnel geometry, TBM tunneling method (EPB or Slurry), soil stratigraphy, water level and geotechnical parameters. Values of the fitting parameters could be taken from the first monitoring measurements and while excavation is in progress, these fitting parameters can be updated allowing a better correlation.

Thus, the proposed equation can be implemented generically in every TBM tunneling project keeping in mind the ground conditions of the area, as well as that the fitting parameters a and b

need to be calibrated for that specific area of study, which can be done by progressively updating the data from monitoring field measures.

ACKNOWLEDGEMENT

The authors are grateful to the Companhia do Metropolitano de São Paulo (METRÔ) for providing and authorizing the use of the data on this study to validate the correlation approach here proposed. The authors would also like to acknowledge the financial support of the Brazilian Research Agency – CNPq, as well as the Foundation for Support of Research DF (FAP-DF) and Institutional Incentive Program Participation in Scientific and Technological Events for Servers of the IFG (PIPECT) of the Federal Institute of Education, Science and Technology of Goiás.

REFERENCES

Anagnostou, G. and Kovári, K. 1996. Face Stability Conditions with Earth-Pressure-Balanced Shields. Tunn. Undergr. Sp. Tech. 11(2), pp.165–173.

Atkinson, J.H. & Potts, D.M. 1977. Subsidence above shallow tunnels in soft ground. Proc. ASCE Geotech. Engng Div. 103 (GT 4), pp. 307-325.

Atkinson, J. 2007. The Mechanics of Soils and Foundations. London: Taylor & Francis, 2nd ed, 475p.

Attewell, P.B. & Woodman, J.P. 1982. Predicting the dynamics of ground settlement and its derivatives caused by tunnelling in soil. Ground Eng. 15(8), pp. 13-22 and 36.

Duncan, J.M. and Chang, C.Y., 1970. Nonlinear analysis of stress and strain in soils. Journal of Soil Mechanics & Foundations Division, 96(5), pp 1629 – 1653.

Fargnoli, V., Boldini, D. & Amorosi, A. 2013. TBM tunneling-induced settlements in coarse-grained soils: The case of the new Milan underground line 5. Tunnelling and Underground Space Technology, Elsevier, 38: 336 – 347.

Guglielmetti, V., Grasso, P., Mahtab, A., & Xu, S. 2008. Mechanized Tunnelling in Urban Areas: design methodology and construction control. London: Taylor & Francis, 528p.

Leca, E., & New, B. 2007. Settlements induced by tunneling in Soft Ground. Tunnelling and Underground Space Technology, Elsevier, 22: 119-149.

Lee, K.M. and Rowe, R.K. 1990. Finite element modelling of the three-dimensional ground deformations due to tunnelling in soft cohesive soils: Part I—Method of analysis. Computers and Geotechnics, 10(2), pp.87-109.

Loganathan, N. & Poulos, H.G. 1998. Analytical prediction for tunneling-induced ground movement in clays. Journal of Geotechnical and Environmental Engineering, 124(9), 846-856.

Kimura, T. and Mair, R. J. 1981. Centrifugal testing of model tunnels in soft clay. Proc. 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, V o l.l, pp. 319-322.

Kool, J.B., Parker, J.C., 1988. Analysis of the inverse problem for transient flow. Water Resources Research 24, 817–830.

Macklin, S.R. 1999. The prediction of volume loss due to tunnelling in overconsolidated clay based on heading geometry and stability number. *Ground engineering*, *32*(4), pp.30-33.

Maidl, B., Herrenknecht, M., Maidl, U. & Wehrmeyer, G. 2012. Mechanized Shield Tunneling. Berlin: Ernst & Sohn, 2nd Edition, 470p.

Mair, R.J. & Taylor, R.N. 1997. Theme lecture: Bored tunnelling in the urban environment. Proc 14th Int. Conf. Soil Mech. & Fdn Engng, Hamburg, 4, pp. 2353-2385.

Mollon, G.; Dias, D. & Soubra, A. H. 2012. Probabilistic analyses of tunneling-induced ground movements. Acta Geotecnica, Springer, 8:181. DOI:10.1007/s11440-012-0182-7.

Peck, R.B. 1969. Deep excavations and tunneling in soft ground, State of the Art Report. Proceedings of the 7th International Conference on SMFE. Mexico City. State of the Art Volume, pp. 225-290.

Repetto, L., Tuninetti, V., Guglielmetti, V. & Russo, G. (2006). Shield tunneling in sensitive areas: A new design approach for the optimization of the construction-phase management. Proc.: World Tunnel Congress and 32nd ITA Assembly. Seoul, Korea.

Rowe, R.K., Lo, K.Y. and Kack, G.J. 1983. A method of estimating surface settlement above tunnels constructed in soft ground. Canadian Geotechnical Journal, 20(1), pp.11-22.

Spiess, A-N. and Neumeyer, N. 2010. An evaluation of R^2 as an inadequate measure for nonlinear models in pharmacological and biochemical research: a Monte Carlo approach. *BMC Pharmacology*, 10:6.

Zhai, Q., Rahardjo, H., 2013. Quantification of uncertainty in soil-water characteristic curve associated with fitting parameters. Eng. Geol. 163, 144–152.