Longitudinal Displacement Profiles for Convergence-Confinement Analysis of Excavations: Applicability to Tunnelling, Limitations and Current Advancement

Nicholas Vlachopoulos
Department of Civil Engineering – Royal Military College of Canada, Kingston, Ontario, Canada

Ya Su
College of Civil Engineering – Hunan University, Changsha, Hunan, China & Department of Geological Sciences and Geological Engineering – Queen's University, Kingston, Ontario, Canada

ABSTRACT

Convergence-confinement method of analysis for tunnelling is a typical approach used in industry for the preliminary analysis of anticipated ground behaviour due to the excavation of a tunnel. This methodology yields an estimate of the load imposed on the support immediately behind the newly excavated tunnel face. Upon excavation, the area immediately behind the face is partially supported by the face itself and does not carry the full load of an open cavity at that moment. Since the inception of this analytical technique, there have been many investigations into the improvement of the Longitudinal Displacement Profile (LDP) in order to address its limitations. The focus of this paper is to describe the technique, guide potential users as to how to apply such an analytical method, to describe the current limitations and how they may be overcome or further investigated.

RÉSUMÉ

La méthode d'analyse du confinement par convergence pour la construction de tunnels est une approche typique utilisée dans l'industrie pour l'analyse préliminaire du comportement du sol anticipé dû l'excavation d'un tunnel. Cette méthodologie fournit une estimation de la charge imposée au support immédiatement derrière la face du tunnel récemment excavée. Lors de l'excavation, la zone immédiatement derrière la face est partiellement supportée par la face elle-même et ne supporte pas la charge totale d'une cavité ouverte à ce moment. Depuis le début de cette technique analytique, de nombreuses études ont été consacrées à l'amélioration du LDP afin de remédier à ses limites. L'objectif de cet article est de décrire la technique, d'indiquer aux utilisateurs potentiels comment appliquer une telle méthode analytique, de décrire les limitations actuelles et de déterminer comment elles peuvent être surmontées ou étudiées plus avant.

1 INTRODUCTION

Tunnel excavation is an intrinsically three-dimensional process that creates complicated stress path within the ground and in turn, to the tunnel-support structure (Vlachopoulos 2009). Estimation of incremental wall deformation and support pressure required for tunnel stability can also be considered a four-dimensional problem due to time-dependent weakening of the rock mass contributing to the force redistribution around the excavation. Most tunnel designs are based on empirical approaches, however, selected designs depend on numerical models or analytical techniques such as the convergence confinement method (CCM).

The CCM is a useful, initial theoretical tool that is used to investigate the mechanical behaviour of the ground during tunnelling, as well the interaction and interplay between the rock mass and the installed support (Figure 1). The CCM consists of three basic components: a. The Longitudinal Displacement Profile (LDP) – describes the relationship between the tunnel deformation with the distance from the tunnel face; b. the Ground Reaction Curve (GRC) – represents the correlation between fictitious internal pressure and tunnel radial displacement; c. the Support Characteristic Curve (SCC) – relates the stress path of installed support to the support strain. This concept was introduced by Fenner (1938) and further refined by various researchers and practitioners (Brown et al 1983; Hoek et al 1980 and1995; Pacher 1964; Panet 1995), and has been comprehensively reviewed by Carranza-Torres and Fairhurst (2000). Since then and during the past two decades, there have been many investigations into the improvement of the LDP in order to address certainly limitations of the overall method. For instance, in most publications the LDP is calculated without consideration of the previously installed support. The purpose of this work is to summarize the development of the LDP in its use for tunnel design as well as to identify continued limitations which still need to be addressed with a view to aiding the tunnel designer in the proper use of this method; these constitute suggestions and future potential research investigations with respect to the CCM.

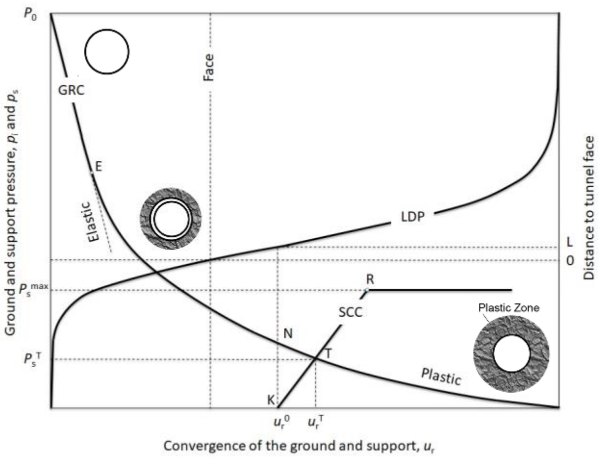

Figure 1. Components of Convergence Confinement Method.

Figure 2. Sequencing of tunnel construction at selected stages; (a) forepoles, (b) installation of forepoles at tunnel face using forepoling machine, (c) view of tunnel face with forepole umbrella inserted, fiberglass dowels, and drainage pipes, (d) shotcrete being applied, (e) controlled excavation of face, (f) excavated material, (g) removal of excavated material, (h) installation of structural support – steel sets, (i) installation of further radial support – grouted rockbolts, (j) successive forepole umbrella seen as well as bench, (k) installation of geomembrane, (l) installation of steel reinforcement for final lining, (m) detail of reinforced final lining, and (n) completed tunnel (Vlachopoulos 2009)

2 THE CONVERGENCE-CONFINEMENT METHOD OF TUNNEL DESIGN

As developed by Carranza-Torres and Fairhurst (2000), the CCM is an analytical, two-dimensional approach that is capable of estimating the load imposed on a support installed behind the face of a tunnel. When a support section is installed in the immediate vicinity of the tunnel face, it does not carry the full load to which it will eventually be subjected to. The face itself carries a significant proportion of the load that is redistributed around the excavation. This is known as the 'face effect' that diminishes as the tunnel face advances away from the face and the installed support. Thus, the support must carry a greater portion of the load than the face had carried beforehand. Once the face is further excavated past the installed support (approx. 2Dl), the support is then effectively subjected to the full design load.

The excavation sequence of the CCM is illustrated in Figure 3 and compliments Figure 1. The initial state, when an unexcavated tunnel section is far ahead of the tunnel face is represented in the right portion of the figure. A 'fictitious' internal pressure P_i, initially equal to the in situ stress, P_0, is applied on the inside of the excavation boundary. At this time, the radial deformation at the boundary u_r is equal to zero since it is assumed that the advancing tunnel has no influence on the rock mass. When the tunnel advances to the excavated face A-A shown in the middle part of the figure labelled "face", the support is installed in the vicinity – at a distance of L behind the face. It is assumed that, provided the face does not advance, the rock mass transmits no load to the support - i.e., $P_s = 0$ at this stage. The extent of plastic yielding and thereby, the boundary deformation is calculated at each stage of the process. As the tunnel advances, the ground and the support deform together and the support receives part of the load that the face had been carrying previously. Once the face of the tunnel has moved behind far enough (the left part of the figure), the internal pressure has fully dissipated such that the excavation boundary condition is of zero normal stress. Moreover, the ground-support system at the reference section is in equilibrium and the support carries the final load P_s^T. At this instant, the face effect has disappeared and the support and ground have converged together by the final amount u_r^T (Carranza-Torres and Fairhurst 2000).

As can be seen from Figure 3, determination of the load transferred from the rock mass to the support requires an interaction analysis of the load-deformation characteristics of the tunnel advancement.

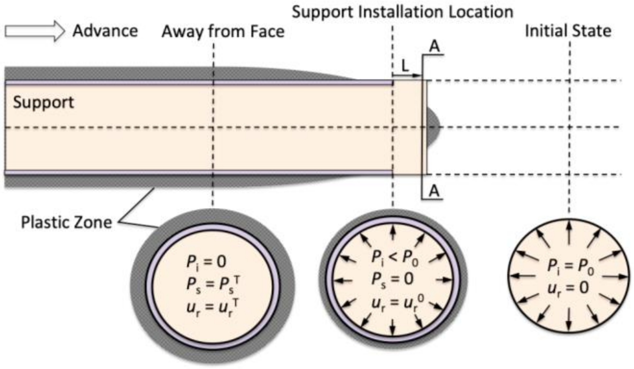

Figure 3. The basic sequence of the convergence confinement method due to progressive advance of the tunnel face

The LDP represents the radial displacement of tunnel sections, which are along the axis of a tunnel and that are located behind and ahead of the face. The effective methods that are applied to compute this profile, including numerical codes and analytical approaches, will be presented in the next section. Figure 1 represents a longitudinal excavation section of an unsupported cylindrical tunnel in the vicinity of the face. The horizontal axis is the radial displacement u_r; the vertical axis on the right is the distance from the analyzed section to tunnel face. At approximately 2-3 diameters behind or ahead of the tunnel face, the effect of the face is negligibly small, and as such, the convergence of the unsupported tunnel section beyond this region approaches a final amount u_r^{max} or is zero (Carranza-Torres and Fairhurst, 2000).

The GRC expresses the increase of the ground radial displacement u_r as a function of the decreasing internal pressure of the tunnel wall P_i. The relationship is related to the mechanical properties of rock mass that is generally constructed from theoretical methods including analytical or semi-analytical elasto-plastic solutions of rock deformation around an excavation based on axial symmetry plane strain assumption. As shown in Figure 1, the GRC extends from where the inner pressure of the ground P_i is equal to the initial stress P_0, and to the final point corresponding to where the inner pressure is equal to zero when the tunnel is unsupported and the maximum possible of the radial displacement, u_r^{max} . Point E corresponds to the tunnel closure at which the ground elastic limit is reached. If the rock internal pressure falls below this limit value, a plastic region extends around the excavation boundary, as shown in Figure 3 (Carranza-Torres and Fairhurst 2000).

The SCC describes the relationship between the internal pressure carried by the support P_s and the radial displacement of tunnel wall u_r as presented in Figure 1. This relationship can be obtained from the geometrical and mechanical properties of the support. When the support is initially installed, the support pressure is zero corresponding to point K, since the assumption that the rock mass transmits no load to the support as long as the face does not advance. Point R corresponds to the case where the support pressure approaches its capacity P_r^{max} and support failure occurs (Carranza-Torres and Fairhurst 2000).

Combination of the analysis of the interaction between the LDP, GRC and SCC enables one to determine the support pressure P_s from the rock mass and the radial displacement of tunnel wall u_r as the tunnel advances.

3 DEVELOPMENT OF THE LONGITUDINAL DEFORMATION PROFILE OVER TWO DECADES

In order to determine the appropriate timing for support installation, it is important to establish the longitudinal displacement profile (LDP) for the tunnel as a function of the distance to the tunnel face (Figure 1). The LDP is initially evaluated using field data by employing the Observational Method and checked with analytical solutions and numerical simulations. There have been selected investigations into the radial displacement of the tunnel wall prior to 2000, ranging from elastic models of the rock mass (Brady and Brown 1993; Corbetta et al 1991; Panet 1993 and 1995) to elasto-plastic studies (Carranza-Torres and Fairhurst 1999; Chern et al 1998; Panet and Guenot 1982; Pelli et al 1991). Within the classic CCM it is assumed that the intrinsic curve of the ground presented by the LDP is independent from the behaviour of tunnel support that has been installed in the previous step.

3.1 The Longitudinal Displacement Profile for Unsupported Tunnels

The magnitude of the tunnel wall closure depends on many factors including the rock mass properties, behaviour, excavation diameter, tunnel shape, in situ stress, groundwater etc. Table 1 summarizes contributions related to the evolution of the LDP for unsupported tunnels over the last two decades, with three categories of considerations, namely ground properties, water effect and other considerations.

3.1.1 Ground Properties

The properties associated with the ground around excavations have been taken into consideration by several authors. In 2000, Carranza-Torres and Fairhurst proposed an analytical solution for the LDP with the Hoek-Brown behaviour of rock mass through two-dimensional symmetric models of circular tunnels subjected to a homogeneous and initial hydrostatic stress condition. This study was conducted without considering the time-dependent weakening of the tunnel due to face advancing. In order to address this issue, Vlachopoulos and Diederichs (2009) proposed a robust solution (V-D equation) considering the effect of the maximum plastic radius around the excavation with respect to the tunnel radial displacement based on the Hoek-Brown criterion with no dilation. The solution consists of three equations separately for tunnel sections ahead of tunnel face, at the face and behind the face. Alejano et al (2010 and 2012) then conducted numerical simulations of tunnels excavated in rock mass with elastic perfectly-plastic (EPP), elastic brittle (EB) and strain softening (SS) behaviour. A set of equations were proposed, estimating the normalized plastic radius under the different types of rock mass behaviours; Together with the V-D equation, this can be used for LDP evaluation. Taking the effect of tunnel face and time-dependent behaviour of soft surrounding rock into consideration, Huang et al (2017) presented the solution of the LDP in the shield region with EPP, linear SS and residual perfectly plastic behaviour of the rock mass, in which the maximum displacement of the ground should be solved beforehand without considering the supporting effect of support structures. Paraskevopoulou and Diederichs (2018) also conducted numerical analyses in order to investigate the effect of tunnel advance and time-dependent behaviour of the rock mass on the total tunnel convergence considering a visco-elastic medium without plastic yield. It was concluded that primary creep plays a dominant role in the initial displacement of the tunnel.

The quality of the rock mass was also taken as a factor of LDP construction by Alejano et al (2012) as an extension of the range of rock mass from its geological strength index (GSI) below 35 to a wider range, i.e. 25 < GSI < 75. Similarly, a s-shaped logistic function was applied by Rooh et al (2018) considering GSI, tunnel diameter and the overburden depth of the tunnel. The EPP constitutive model of the rock mass was conducted in the numerical modelling. Predictive equations for assessing the normal radial displacement were presented by Basarir et al. (2010), applying a multiple regression modelling, on the basis of Rock Mass Rating (RMR) covering a range 20 < RMR < 50. Aiming to broaden the range of rock mass from weak quality to an average quality, numerical codes were adopted by Wu et al (2015) based on the generalised Hoek-Brown model of the material. Fitting functions were presented on the basis of basic quality (BQ) indices of the rock mass.

3.1.2 Water Effect

Water seepage is one of the hydro-mechanical factors that affect tunnels driven in a saturated ground. By considering the water effect on deep circular unsupported tunnels in an elastic rock mass with steady-state water seepage, Nam and Bobet (2007) proposed analytical formulations of normalized LDP curve for both dry and saturated ground. Aiming to determine the effect of groundwater flow, Shin et al. (2014) modelled deep circular tunnels with elasto-

Table 1 Summary of contributions for the LDP for unsupported tunnels over the last two decades

REFERENCE	ROCK MASS BEHAVIOUR	METHOD OF ANALYSIS	PREDICTED RESULTS	RESEARCH REMARKS
Ground Properties				
Carranza-Torres & Fairhurst (2000)	Elasto-plastic (HB)	3D symmetric FD	LDP	Closed form solution without considering time-dependent weakening of the rock mass
Vlachopoulos & Diederichs (2009)	Elasto-plastic (HB)	2D symmetric FE, 3D symmetric FD	Separate normalized LDPs based on x/D	Analytical functions (V-D equation) considering plastic radius with no dilation
Alejano et al (2010)	SS (MC, HB)	2D FD analysis	LDP	Numerical analysis considering the effect of strain-softening behaviour and dilatancy of rock mass without residual parameters
Basarir et al (2010)	EPP (HB)	3D axisymmetric FD	Separate normalized LDPs based on x/D	Prediction system based RMR value of 20 - 50, with no volume change of the rock mass, presented in two parts based the relative distance to tunnel face
Alejano et al (2012)	EPP, SS (MC, HB)	2D symmetric FD, 3D axisymmetric FD	Normalized plastic radius	Equations for rock mass of GSI value at 30-75 can be used together with V-D equation
Wu et al (2015)	Elasto-plastic (HB)	3D axisymmetric FD	Separate normalized LDPs based on x/D	Fitting equations based BQ indices of the rock mass, considering the effect of tunnel depth
Huang et al (2017)	Constitutive model of five stages (Huang et al 2015)	Analytical analysis	CCM curves	Solution for the tunnel convergence in the shield region during TBM tunneling, considering the effect of both tunnel face and the time-dependent behaviour of ground
Paraskevopoulou & Diederichs (2018)	Visco-elastic without plastic yield	2D axisymmetric FD	LDP	Numerical analyses considering both tunnel advance and time-dependent behaviour of the rock mass, without considering the influence of time-dependency resulting in delayed deformation
Rooh et al (2018)	EPP (MC)	3D axisymmetric analysis	Separate LDPs based on GSI range	Sigmoidal function for GSI value of 20-60, lower than 20 and higher than 60, considering tunnel diameter and tunnel depth
Water Effect				
Nam & Bobet (2007)	Elastic	3D axisymmetric FE	Separate normalized LDPs based on x/D	Analytical formulations for both dry and saturated ground conditions, considering steady-state groundwater flow
Shin et al (2014)	Elasto-plastic (MC)	3D axisymmetric FE	Both radial and axial LDPs	Numerical analyses considering the effect of groundwater flow, with a back-analysis method proposed to estimate geotechnical parameters
Prassetyo & Gutierrez (2018)	Elastic	2D axisymmetric FD	Separate normalized LDPs based on x/D	Numerical model considering nonlinear unloading factors; Equation containing time-dependent constants
Bour & Goshtasbi (2019)	EPP, SS (MC)	2D FD, 3D FD	CCM curves	Numerical analyses with different conditions: saturated or dry condition, different post-failure behaviour of the rock mass and various values of in situ stress ratio
Other Considerations				
Unlu & Gercek (2003)	Linear elastic	3D axisymmetric FD	Separate normalized LDPs based on x/D	Analytical solution considering Poisson's ratio of rock mass
Zhang et al (2008)	Elastic, elastic-plastic (MC)	3D symmetric DE	The displacement ration versus distance behind the face	Numerical analyses considering horse-shoe shaped tunnels under two-stage excavation condition, without considering time-dependent behaviour of the rock mass; Fitting function for the LDP behind the face containing two fitting parameters
Sadeghiyan et al (2016)	Elasto-plastic behaviour of soil (MC)	3D symmetric analysis	Normalized LCP	Concept "Longitudinal Convergence Profile" (LCP) is regarded as alternative to the LDP, considering soil strength parameters; LCP relations proposed for different soil parameters

plastic behaviour of the rock mass to obtain both the radial and axial LDPs. A back analysis then was used in order to estimate the geotechnical parameters based on the result that the LDP is strongly affected by the groundwater flow. Recently, Prassetyo and Gutierrez (2018) investigated the effect of transit hydro-mechanical response on deep saturated ground surrounding an advancing tunnel, using two-dimensional numerical simulations with non-linear unloading factors. They also proposed a set transit LDP equation, including time-dependent constants, to predict transit radial displacement of the tunnel. Bour and Goshtasbi (2019) compared the numerical modelling simulation results of a circular tunnel in a saturated medium with its dry condition. Two types of constitutive models, namely the EPP and SS were used. A limitation that still exists, however, is that LDPs considering the pore pressure effect in conjunction with EPP and SS behaviour of the rock mass are not currently available that could be utilized.

3.1.3 Other considerations

Other factors related to the LDP have also been investigated by selected authors. With respect to linear elastic behaviour of the rock mass, Unlu and Gercek (2003) analyzed the effect of Poisson's ratio using numerical modelling. The cutting functions in which Poisson's ratio was used were presented for three segments of the tunnel, similar to the V-D equation. A new concept "Longitudinal Convergence Profile" regarded as an alternative to the LDP was suggested by Sadeghiyan et al (2016). Numerical simulations were adopted considering soil strength parameters with elasto-plastic behaviour of the medium. Various LDP relations for different soil parameter values, namely elasticity modules, cohesion, and angle of internal friction were introduced based the summation of absolute displacement for the crown and invert of the tunnel walls. Focusing on the convergence of the side walls of tunnels, a function, defined as the displacement ratio versus distance behind the face, was proposed by Zhang et al (2008). This was based on numerical modelling of horseshoe shaped tunnels excavated by two-stage excavation compared to that of full face excavation. By using a fitting function and the Self Similarity Principle, he analysed the influence of horizontal stress and strength parameters.

3.2 The Longitudinal Displacement Profile For Supported Tunnels

The contributions related to the evolution of the LDP for supported tunnels over the last two decades are summarized and listed in Table 2. Due to the fact that support structure definitely plays an important role in tunnel excavation, in recent years selected attempts have been made to introduce a 'supported LDP'. Oke et al (2013) proposed a modified version of the V-D equation, considering the influence of support interaction. The modified LDP can be created through an iterative process in combination with numerical modelling results. Taken as an indicator of the self-supporting capacity of the rock mass, this 'fictitious' support pressure surrounding the tunnel face was investigated by Cui et al (2015), on the basis of a numerical approach modified according to three different types of constitutive models, namely the EPP, EB and SS rock masses. The modified numerical solution can be used in combination with the V-D equation to evaluate the LDP. Almog et al (2015), within the framework of the convergence–confinement method, developed an analytical elasto-plastic solution, evaluating the LDP curve for the inclusion of Tunnel Boring Machine (TBM) pressure for soft tunnel ground, through which both ground movement and lining forces are addressed. On the basis of Mingyazi Tunnel excavated in a weak rock mass, both the vertical and horizontal displacement are measured as field data (Luo et al 2018). The LDPs for this tunnel were created through numerical simulations, in which the three beaches construction method was used, assuming the decrease in the beaches length and change of the geologist of primary support.

In contrast, not considering the support mechanics but the excavation-support increments and timing and location of support during installation (Figure 4), Oke et al (2018) proposed a methodology and solution for improving the CCM used within squeezing ground conditions (i.e. weak rock masses) at depth for three excavation methods, namely, TBM, conventional and drill and blast. Numerical simulations were conducted to obtain fitting curves of the LDP and their curve-fit variables. Figure 4 illustrates the importance of the timing associated with support installation as well as the support location wrt tunnel convergence. As can be seen, at the face, the installed early support carries a significantly higher load at equilibrium than the delayed support. This may result in support overloading.

A version of a Sigmoid function was developed by Vlachopoulos and Diederichs (2014) to provide a LDP function of support installation position and the distance to the tunnel face. This function is a best fit for the LDP curves plotted using supported and unsupported simulations under elastic and elastic perfectly-plastic conditions. A case study was conducted by Su et al (2018), in which supported LDPs were plotted using numerical modelling, with the assumption of various excavation increments as well as the installation timing of support structure. The LDPs obtained in this study combined with other CCM components were used to calculate the factor of safety of the support in order to develop an evaluation method to figure out the cause of support failure in Liziping Tunnel. For the purpose of determining the optimal installation location of initial support, Zhang et al (2019) improved an LDP equation for estimating the evolution of the wall convergence at unexcavated tunnel sections, and introduced a method that adopts the excavating releasing ratio and the tunnel convergence increment. Numerical simulations of tunnels were used in which the rock mass obeys the Mohr-Coulomb criterion with tension cut-off.

Considering the variation of pre-deformation as part of the LDP of tunnel ground, Song et al (2016) analyzed the measured crown settlement for Qingdao subsea tunnel via the regression analysis method, and calculated the supported LDPs employing and numerical calculations. Wang et al (2019) implemented a field test of deformation characteristics of Beishan Exploration Tunnel surrounded

Table 2 Summary of contributions to the longitudinal displacement profile for supported tunnels over last two decades

REFERENCE	ROCK MASS BEHAVIOUR	METHOD OF ANALYSIS	PREDICTED RESULTS	RESEARCH REMARKS
Oke et al (2013)	EPP (HB)	3D axisymmetric FD	Normalized LDP	Solution modified from V-D equation, considering the effect of temporary support consisted of shotcrete thicknesses and rock bolts
Vlachopoulos & Diederichs (2014)	Elastic, EPP (MC)	2D FE, 3D symmetric FD	LDP	Sigmoid function providing a best fit LDP as a function of face distance and support installation position
Almog et al (2015)	Elasto-platic (MC)	Analytical analysis (case study)	LDP	Analytical solution for the inclusion of TBM pressure without considering viscosity, in which the relaxation factor is derived from CCM curves
Cui et al (2015)	EPP, EBP, SS	Numerical analysis	Plastic radius	Numerical approach to maximum plastic radius can be used together with V-D equation, considering the fictitious support pressure
Song et al (2016)	EPP (MC)	3D symmetric FD (case study)	LDP	Numerical simulations estimating the crown and horizontal settlement of the ground; Solid-fluid coupling model test predicting the lagged displacement and displacement loss based the regression analysis
Luo et al (2018)	Elasto-plastic (MC)	3D FD (case study)	The crown and horizontal settlements	Numerical modelling considering various construction schemes, in which tunnel deformation parameters are obtained based displacement back analysis
Oke et al (2018)	EPP with dilation at zero	2D axisymmetric FE	Normalized LDP	Improved solution for supported tunnels with various excavation-support increments and unsupported tunnel lengths, without considering the effect of installed support
Su et al (2018)	Elasto-plastic (HB)	3D symmetric FD (case study)	LDP	Numerical analyses for a horseshoe shaped tunnel case under different construction schemes with support installed during excavation
Wang et al (2019)	Elasto-plastic (HB)	Field test	Tunnel convergence	Field test for hard rock; Lee, Hoek and V-D equation for LDP calculation are generalized to be in use of estimating tunnel loss displacement as part of the total convergence
Zhang et al (2019)	Elasto-plastic with tension cut-off (MC)	3D FD	Separate normalized LDPs based on x/D	Improved solution of the LDP at unexcavated tunnel sections; Method for deriving the installation location of initial support adopts the excavating releasing ratio

by hard rock during excavation process. Three solutions of the LDP, namely Lee, Hoek and V-D equation are generalized from their uniform version and are used to estimate the loss displacement. These are then compared with the fitted curves from field data in order to obtain the optimal estimation equation.

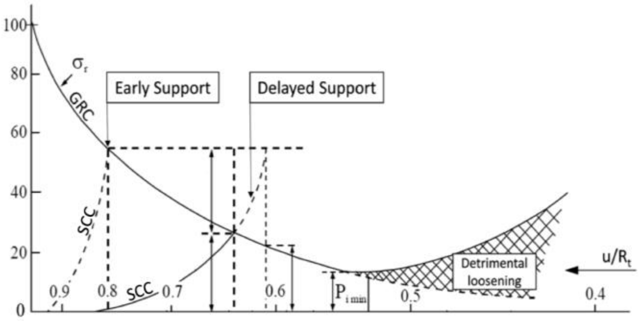

Figure 4. The Ground Reaction Curve (GRC) and Support Characteristic Curve (SCC) relationship. σ_r = radial stress and P_{imin} = minimum internal pressure before detrimental loosening (Oke et al 2018).

4 DISCUSSION POINTS, CONCLUSIONS AND RECOMMENDATIONS

When utilizing any analytical or numerical model, a tunnel designer must ensure that the proper tool is being utilized for the proper scenario that is being evaluated. This is certainly the case with the use of the CCM and the LDP as an initial determination of how to design a tunnel excavation. There are many assumptions and limitations associated with this method that the users must realize and incorporate in their use of the method as well as in the design. As such, the authors have summarized the research associated with the current state and development of the LDP for underground excavations over the last two decades with a view of consolidating such literature (Table 1 and 2) and to identify the issues, assumptions and limitations associated with its use. There are two broad categories of LDPs – unsupported and supported. The categories were primarily based on the inclusion (or not) of temporary support within the tunnel design. Most of the studies assumed an isotropic, homogeneous material along either vertically or horizontally. The proposed analytical functions for evaluating the LDP were primarily utilizing a circular tunnel opening, the validity of which may be reduced for non-circular tunnels (Vlachopoulos and Diederichs 2014).

Panet (1993, 1995), Panet and Guenot (1982), Chern et al. (1998) and others have proposed empirical solutions for LDP's based on elastic modelled deformation of varying intensity (correlated to various indices such as the ratio between in-situ stress and undrained cohesive strength, for example). Alternatively, an empirical best fit to actual measured closure data can be used (i.e. based on data from Chern et al, 1998). These solutions are shown in Figure 5. These classical solutions are related to the scenario depicted in Figure 6a. However, weaker rock materials yield a much larger plasticity zone as seen in Figure 6b. As such, one must determine the scenario that is most applicable to their site-specific tunnelling conditions and chose an analysis that is relevant to those circumstances. There is certainly a correlation between the accumulation of radial displacement and the development of the plastic yield zone during tunnel excavation. However, in selected studies (Panet 1995; Unlu and Gercek 2003), the yield zone at the tunnel face is assumed to have no interaction with the developing yielding zone in the ground as demonstrated in Figure 6. Therefore, there is an explicit requirement to take into consideration the extent and influence of the increased overall yielding (that are interacting at the face and sidewalls as described in Vlachopoulos and Diederichs (2009).

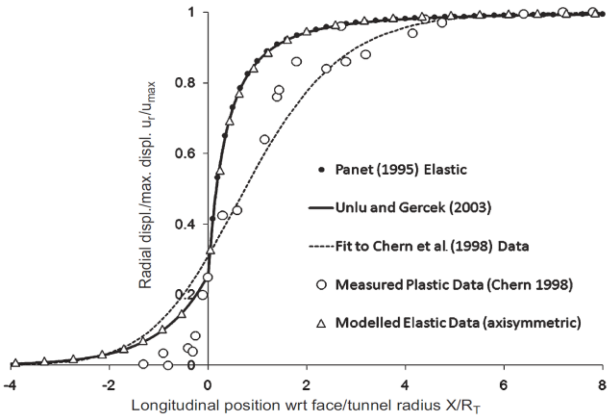

Figure 5. Comparison of classical Longitudinal Displacement Profiles (LDPs) (Vlachopoulos and Diederichs 2009).

Tunnel support installation (type and timing) also plays an important role within the CCM. If the support was to be installed too early, it may be at risk of overloading the support. On the other hand, support installed too late is ineffective as convergence and stress reorientation has already taken place. Therefore, the timing of the addition of the support is a crucial factor. The inclusion of support (i.e. supported LDP) must be a consideration when utilizing the CCM. At the moment, most methods utilizing an LDP are calculated without taking into consideration the installation of the support in a stage-wise fashion. The support near the face definitely influences the stress conditions and therefore, the displacements in and around the face, thus, influencing the LDP of the tunnel. For LDPs that take into consideration support, these methods have generally been developed based on numerical analysis or case studies. However, few studies proposed empirical solutions for calculating the supported LDP. Thus, the empirical function of the LDP must be adjusted to include such cases. In addition, the application of the LDP must be extended to include multiple geometries, anisotropy, water as well as other considerations. These are all lines of investigation that can be undertaken in the future.

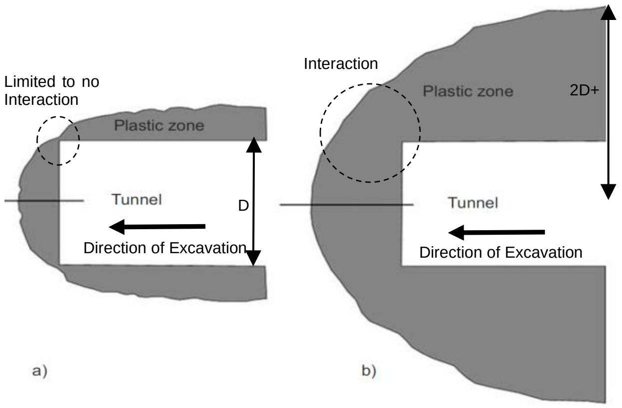

Figure 6. a) Plastic yield zone developing as tunnel advances. Maximum plastic zone radius is less than twice the tunnel radius and the wall yield zone does not interact with the face yield zone (Panet's 1995 longitudinal displacement profile is valid); b) wall yield zone more than double the tunnel radius and interacts with face yield zone (Panet's longitudinal displacement profile is not valid) (modified after Vlachopoulos and Diederichs 2009)

5 REFERENCES

Alejano, L.R., Rodríguez-Dono, A., Veiga, M. 2010. Preliminary assessment of longitudinal deformation profiles for tunnels excavated in strain-softening rock masses. Rock Mechanics in Civil and Environmental Engineering - Proceedings of the European Rock Mechanics Symposium, EUROCK 2010.

Alejano, L.R., Rodríguez-Dono, A., Veiga, M. 2012. Plastic radii and longitudinal deformation profiles of tunnels excavated in strain-softening rock masses. Tunnelling and Underground Space Technology 30: 169-182.

Almog, E. and Mangione, M. 2015. Ground relaxation in segmental lining design using the convergence-confinement method. Underground Design and Construction Conference IOM3 Hong Kong Branch.

Basarir, H., Genis, M., Ozarslan, A. 2010. The analysis of radial displacements occurring near the face of a circular opening in weak rock mass. International Journal of Rock Mechanics and Mining Sciences 47(5): 771-783.

Bour, K. and Goshtasbi, K. 2019. Study of convergence confinement method curves considering pore-pressure effect. Journal of Mining and Environment 10(2): 479-492.

Brady, B.H.G., Brown, E.T. 1993. Rock Mechanics for Underground Mining. Second ed. Chapman and Hall, London

Brown, E.T., Bray, J.W., Ladanyi, B., Hoek, E. 1983. Ground response curves for rock tunnels. J Geotech Eng ASCE 109:15–39.

Carranza-Torres, C. and Fairhurst, C. 1999. The elasto-plastic response of underground excavations in rock masses that satisfy the Hoek-Brown failure criterion. Int. J. Rock Mech. Min. Sci. 36(6): 777–809.

Carranza-Torres, C. and Fairhurst, C. (2000). Application of the convergence-confinement method of tunnel design to rock masses that satisfy the hoek-brown failure criterion. Tunnelling and Underground Space Technology incorporating Trenchless Tech Research,15(2): 187-213.

Corbetta, F., Bernaud, D., Nguyen-Minh, D. 1991. Contribution a la `methode convergerce–confinement par le principe de la similitude. ´ Rev. Fr. Geotech. 54: 5–11.

Chern, J.C., Shiao, F.Y., Yu, C.W. 1998. An empirical safety criterion for tunnel construction. Proceedings of the Regional Symposium on Sedimentary Rock Engineering, Taipei, Taiwan, pp. 222–227.

Cui, L., Zheng, J.J., Zhang, R.J., Lai, H.J. 2015. A numerical procedure for the fictitious support pressure in the application of the convergence–confinement method for circular tunnel design. International Journal of Rock Mechanics and Mining Sciences 78: 336-349.

Fenner, R. 1938. Untersuchungen zur Erkenntnis des Gebirgsdruckes. Gli~ckauf 74: 681-695 and 705-715.

Hoek, E., Brown, E.T. 1980. In: Underground excavations in rock. London: Chapman & Hall.

Hoek, E. and Brown, E.T. 1988. The Hoek-Brown failure criterion - a 1988 update. Proc. 15th Canadian Rock Mech. Symp. (ed. J.C. Curran), 31-38. Toronto, Dept. Civil Engineering, University of Toronto

Hoek, E, Kaiser, P.K., Bawden, W.F. 1995. Support of underground excavations in hard rock.Rotterdam: Balkema.

Huang, X., Liu, Q.S., Kang, Y.S., Liu, J.P., Pan, Y.C. 2015. Constitutive model of squeezing deformation tunnelling in deep soft ground. In International Conference on Tunnel Boring Machines in Difficult Grounds. Singapore.

Huang, X., Liu, Q.S., Peng, X.X., Lei, G.F., Liu, H. 2017. Mechanism and forecasting model for shield jamming during TBM tunnelling through deep soft ground. European Journal of Environmental and Civil Engineering.

Luo, Y., Chen, J., Chen, Y., Diao P., Qiao X. 2018. Longitudinal deformation profile of a tunnel in weak rock mass by using the back analysis method. Tunnelling and Underground Space Technology 71: 478-493.

Nam, S.W. and Bobet, A. 2007. Radial Deformations Induced by Groundwater Flow on Deep Circular Tunnels. Rock Mech. Rock Engng 40: 23.

Oke, J., Vlachopoulos, N., Diederichs, M. S. 2013. Modification of the Supported Longitudinal Displacement Profile for Tunnel Face Convergence in Weak Rock. 47th U.S. Rock Mechanics/Geomechanics Symposium. San Francisco, California, American Rock Mechanics Association: 8.

Oke, J., Vlachopoulos, N., Diederichs, M. 2018. Improvement to the Convergence-Confnement Method: Inclusion of Support Installation Proximity and StifnessM. Rock Mech Rock Eng 51: 1495.

Pacher F. 1964. Deformationsmessungen in Versuchsstollen als Mittel zur Erforschung des Gebirgsverhaltens und zur Bemessung des Ausbaus. Felsmechu Ing Geol 1: 149–61.

Panet, M. 1993. Understanding deformations in tunnels. In: Hudson, J.A., Brown, E.T., Fairhurst, C., Hoek, E. (Eds.), Comprehensive Rock Engineering, Vol. 1. Pergemon, London, pp. 663-690.

Panet, M. 1995. Calcul desTunnelspar la Methode de Convergence – ´Confinement. Presses de l'Ecole Nationale des Ponts et Chaussees, 178 pp, Paris.

Panet, M. and Guenot, A. 1982. Analysis of convergence behind the face of a tunnel. Proceedings, International Symposium Tunnelling 82, IMM, London, pp. 197–204.

Paraskevopoulou, C. and Diederichs, M. 2018. Analysis of time-dependent deformation in tunnels using the Convergence-Confinement Method. Tunnelling and Underground Space Technology 71: 62-80.

Pelli, F., Kaiser, P.K., Morgenstern, N.R. 1991. The influence of near face behaviour on monitoring of deep tunnels. Can. Geotech. J. 28: 226–238.

Prassetyo, S.H. and Gutierrez, M. 2018. Effect of transient coupled hydro-mechanical response on the longitudinal displacement profile of deep tunnels in saturated ground. Tunnelling and Underground Space Technology 75: 11-20.

Rooh, A., Nejati, H.R., Goshtasbi, K. 2018. A new formulation for calculation of longitudinal displacement profile (LDP) on the basis of rock mass quality. Geomechanics and Engineering 16(5): 539-545.

Sadeghiyan, R., Hashemi, M., Moloudi, E. 2016. Determination of longitudinal convergence profile considering effect of soil strength parameters. International Journal of Rock Mechanics and Mining Sciences 82: 10-21.

Shin, Y.J., Kim, D.H., Lee, I.M. 2014. Numerical Simulation of Seepage-induced Behaviour of Tunnel for Analyzing Deformation Characteristic and Estimating Geotechnical Parameters. KSCE J Civ Eng 18: 659.

Song, S.G., Li, S.C., Li, L.P., Zhang, Q.Q. 2016. Study on Longitudinal Deformation Profile of Rock Mass in a Subsea Tunnel. Marine Georesources & Geotech 34(4): 376-383.

Su, Y., Su, Y., Zhao, M., Liu, S., Li, X. 2018. A case study of the failure of Liziping tunnel. Tunnelling and Underground Space Technology 80: 301-312.

Unlu, T. and Gercek, H. 2003. Effect of Poisson's ratio on the normalized radial displacements occurring around the face of a circular tunnel. Tunnelling and Underground Space Technology 18(5): 547-553.

Vlachopoulos, N. 2009. Back Analysis Of a Tunnelling Case Study in Weak Rock of the Alpine System in Northern Greece: Validation and Optimization of Design Analysis Based on Ground Characterization and Numerical Simulation. Kingston, Ontario: Queens University.

Vlachopoulos, N. and Diederichs, M. 2009. Improved Longitudinal Displacement Profiles for Convergence Confinement Analysis of Deep Tunnels. Rock Mech Rock Eng 42: 131.

Vlachopoulos, N. and Diederichs, M.S. 2014. Appropriate Uses and Practical Limitations of 2D Numerical Analysis of Tunnels and Tunnel Support Response. Geotech Geol Eng 32: 469.

Wang, J., Li, E.B., Chen, L., Wang, J., Tan, Y.H., Duan, J.L., Pu, S.K., Gao, L., Han, Y., Wang C.L. (2019). Measurement and analysis of the internal displacement and spatial effect due to tunnel excavation in hard rock. Tunnelling and Underground Space Technology 84: 151-165.

Wu, S.C., Geng, X.J., Gao, Y.T., Zhao, G.J. 2015. A study of the longitudinal deformation of tunnels based on the generalized Hoek-Brown failure criterion. Rock and Soil Mechanics 1000-7598 (2015) 04-0946-08 (in Chinese).

Zhang, P., Yin, J.J., Nordlund, E., Li, N. 2008. Determination and verification of the longitudinal deformation profile in a horse-shoe shaped tunnel using two-stage excavation. 5th International Conference and Exhibition on Mass Mining, Luleå Sweden 9-11.

Zhang, Y.J., Su, K., Qian, Z.D., Wu, H.G. 2019. Improved Longitudinal Displacement Profile and Initial Support for Tunnel Excavation. KSCE J Civ Eng.