

Analysis of Mechanized Shield Tunnel Linings with the Advanced Displacement-Confinement Method

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ABSTRACT

The design of tunnel linings in soft ground presents a complex challenge, requiring a balance between stability, constructability, and cost-efficiency. Analysis methods are required to account for real soil behaviour, the evolving ground load path, or displacement fields — factors heavily influenced by tunnel boring machine (TBM) geometry and confinement pressures. Capturing this process properly is normally acknowledged to require production of 3D soil-structure numerical models with detailed consideration of the TBM advance and components. The Advanced Displacement-Confinement Method (ADCM) is a semi-analytical, non-iterative procedure that explicitly captures the interaction between TBM operations, soil behaviour, and lining response. It consists of two novel mathematical models / algorithms (SHIELD and RINGS) that are integrated to account for TBM confining pressures, shield geometry, and the anisotropic displacement and stress fields around the tunnel. This paper evaluates the method's application for the segmental tunnel lining design through comparative analysis via two 2D modelling approaches: A simplified elastic analysis and a detailed numerical model. This is done using unfactored and factored inputs from the ADCM for the ground loading or relaxation respectively, avoiding 3D modelling of the TBM tunnelling process and remaining compliant with design codes. A case study back analysis which included direct monitoring of lining demands with TBM operation and settlements is presented. Results show that both analysis approaches achieve sufficient accuracy indicating that routine 3D modelling can be optional for typical cases, while preserving reliable lining design. In addition, the method uniquely facilitates extensive parametric studies and factored design loading via a focused process for ground parameter and TBM confining pressure adjustments, enhancing safety, efficiency and consistency.

1 INTRODUCTION

A key to the success of soft ground shield tunnelling in urban settings lies on the quality of the lining design and TBM operations: designers must translate controllable TBM parameters into reliable ground loads, stiffness, and ring actions while maintaining settlement control and constructability (Maidl, et al., 2012). Semi-empirical and elastic analytical approaches predict settlements from assumed ground loss (O'Reilly & New, 1982; Sagaseta, 1987; Verruijt & Booker, 1996; Loganathan, et al., 2000) but they do not return lining forces nor quantify how face pressure, grout pressure, and shield gap drive those demands, despite being known to be critical parameters for correctly capturing the ground response (Cording, 2018). Classical Convergence-Confinement Method (CCM) formulations (Panet & Guenot, 1983; Vrakas, 2016; Vrakas, et al., 2018; Lee, 2018) or closed form structural analytical solutions (Einstein & Schwartz, 1979; Duddeck & Erdmann, 1985; Carranza-Torres, et al., 2013) provide insight into ground loading or lining forces but similarly neglect the TBM operation and shield interaction or rely on simplified soil models and cannot be used to obtain anisotropic loading on the tunnel lining. Full 3D numerical models (Kasper & Meschke, 2004) are powerful yet computationally costly and difficult to align with code-based partial factors and consistent workflows (Yeow & Katsigiannis, 2024).

The Advanced Displacement-Confinement Method (ADCM) is a recently developed (Almog-Goldreich & Fuentes, 2025) semi-analytical framework for design of mechanized shield tunnels. The key premise of the ADCM, is that both ground and lining deformations can be captured with sufficient accuracy, if the confinement provided by the TBM is correctly simulated in a plane-

strain analysis. The method is conceived either as a stand-alone design tool or a complimentary tool for numerical modelling and includes several analytical steps.

In this paper, we discuss how to apply the concepts of the ADCM for analysis of the Precast Concrete Tunnel Lining (PCTL) in a framework fully compatible with recognized industry standards or adopting a partial factor design approach. We evaluate and demonstrate the ADCM analysis approach with a case history demonstrating its accuracy and practicality.

2 TBM CONFINEMENT AND GROUND RESPONSE

The ADCM consists of two novel analytical models / algorithms that together with existing standard analysis methods establish a direct link from TBM design and confining pressures (lower / upper bound and optimal) → ground convergence and loads → lining demands (unfactored / factored) → settlement control and monitoring. This focuses attention on the critical aspects of the tunnel drive to allow a clear design path and parametric analysis which enhance both safety and efficiency. Full details on ADCM can be found in (Almog-Goldreich & Fuentes, 2025).

2.1 TBM Confinement: Soil-Hydraulic Initial Equilibrium and Load Distribution (“SHIELD”)

The SHIELD model constitutes a circumferential confinement closed-form solution that integrates TBM pressures (face and grouting) around the advancing shield and provides an anisotropic ground relaxation to be used in a 2D plane strain analysis.

The governing equation for the TBM circumferential confinement pressure takes the face pressure and boosts it by the backfill grout pressure as follows:

$$P_{SHIELD}(\theta) = \left(P_{TBM} - \frac{D_{exc} \cdot \gamma_{bt} \cdot \cos \theta}{2} \right) + \frac{\Delta P^2 \cdot \pi \cdot D_{exc}}{P_{TBM} \cdot L_s \cdot f(\theta)} \cdot f(\theta) \leq P_g \quad (1)$$

Where: P_{TBM} is the TBM face pressure at springline, θ is the angular position around the shield, D_{exc} is the shield diameter, and γ_{bt} is the unit weight of the bentonite or slurry, ΔP as the difference between grout and face pressures which is dependent on the advance rate, L_s is the length of the shield, and $f(\theta) = [(1 - \cos \theta)/2^{m_g}]$ is a shape function for the grout distribution, which mean value is $\bar{f}(\theta)$. The empirical parameter m_g has been found to be equal to 0 for EPB machines and 1 for Slurry machines. By definition, the calculated pressure must be less or equal to the grouting pressure P_g .

The TBM confinement ratio forms a relaxation parameter analogous to the long-used CCM relaxation constant in rock tunnelling. In addition, it can be utilized as an index that quantifies the adequacy of the chosen TBM earth and grout pressures. It can be defined as:

$$\lambda_{TBM}(\theta) = 1 - \frac{P'_{SHIELD}(\theta)}{P'_{Soil}(\theta)} \quad (2)$$

Where the effective TBM confinement: $P'_{SHIELD}(\theta) = P_{SHIELD}(\theta) - u_w(\theta)$; the effective ground stress: $P'_{Soil}(\theta) = 0.5[(\sigma'_v + \sigma'_h) - (\sigma'_h - \sigma'_v) \cos 2\theta]$ with $u_w(\theta)$ the hydrostatic pore pressure around the tunnel and σ'_v and $\sigma'_h = K_{TBM} \sigma'_v$ are the average effective soil stresses prior to tunnelling. K_{TBM} is the mobilized horizontal stress ratio which is between the in-situ (K_0) and active (K_a) coefficients per DAUB (2016) and is usually between 0.3 and 0.5.

2.2 Ground Response: Radial Increments of Nonlinear Ground Stabilization (“RINGS”)

RINGS is an explicit incremental solution to the ground response as a function of the TBM and soil parameters. It utilizes the principles of the CCM with a constitutive law referred to as the Mohr-Coulomb with Shear Hardening (MCSH), which bridges the gap between the overly simple Mohr-Coulomb and the more computationally demanding Hardening Soil model and incorporates the interaction with the TBM shield. The algorithm avoids a numerical iterative solver by calculating the plastic strains via radial increments from the far field to the tunnel extrados. The RINGS algorithm, MCSH model behavior and output displacement field are illustrated in Figure 1 below.

The solution produces realistic stress and displacement fields around the tunnel and directly obtains ground stiffness and loads on the lining as well as the volume loss which can be used for surface settlement assessments.

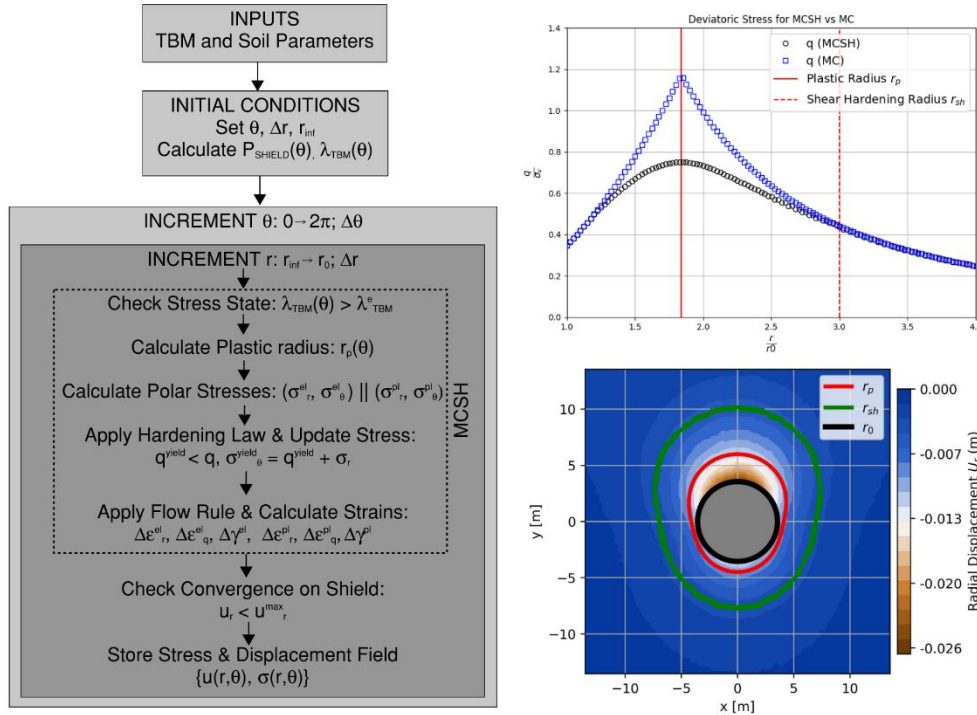


Figure 1. RINGS algorithm pseudo-code (left); Comparison of the MCSH and MC deviatoric stress field (top right) and example of RINGS displacement field output for a 7m diameter tunnel with 1D cover and 2bar of average internal SHIELD pressure; $\lambda_{TBM}(\theta = 0^\circ) \sim 0.93$.

3 ANALYSIS OF LINING

3.1 Earth Pressures and Load Factors

Earth pressures are soil loads that act on the precast concrete tunnel lining (PCTL) throughout its design life. The ITA Working Group 2 Report (2019) provides recommendations on the analysis to obtain ground and water pressures and the load factors and combinations referred to as “service stage loads”. These are defined in a similar fashion to well-known codes and guidelines (OVBB, 2011; ACI-544.7R, 2016; PAS-8810, 2016; ITA-WG2, 2019; LRFDTUN-1, 2017). The effective stress earth pressure is generally divided into the vertical (EV) and horizontal (EH) components, where EH is either the active or at-rest horizontal earth pressures with a partial load factor (typically set as 1.35). The water loading (WA) is often only factored up for the buoyancy check, although some codes require this for other load cases.

While it is generally established in most standard guidance that numerical analysis is recommended to capture the soil-structure interaction properly, the definition and methodology of such an analysis is loosely defined. In addition, LRFDTUN-1 points that commercially available numerical modelling software may not permit the input of factored loads and that a rational method for incorporating the load factors into the analysis must be developed by the Engineer.

With the SHIELD and RINGS algorithms, the ADCM enables to obtain the soil loading and ground deformations as a direct function of the TBM operation in a 2D semi-analytical non-iterative analysis. The design engineer is then given flexibility in choosing the most appropriate form of structural analysis, whether analytical or numerical. In this paper we demonstrate how to implement the ADCM for lining design using two approaches which are commonly adopted for the structural analysis of tunnel (ITA-WG2, 2019):

1. Bedded spring or elastic continuum model using factored EV and EH as direct inputs. This can be done either using a structural software or a closed form analytical solution.

2. Multi-stage 2D soil-structure continuum elasto-plastic numerical model in a Finite Elements (FE) or Finite Difference (FD) code utilizing the concept of ground relaxation (i.e. stress reduction method) followed by installation of the PCTL. The analysis in this case is run unfactored with partial factors applied to the resulting forces and moments in the lining.

In summary in Approach 1, we obtain the loading and stiffness from RINGS and apply it to a 2D elastic continuum closed form solution. Approach 2 is a detailed soil 2D soil-structure numerical FE model using an advanced constitutive model with the two tunnels excavated sequentially with a global relaxation value is obtained from RINGS. The following sections will elaborate on each of these methodologies and compare to a recent case study in which direct monitoring of the lining demands was conducted.

3.2 Approach 1: Elastic Bedded-Spring Model or Continuum Closed Form Solution

This methodology is demonstrated here through the classic closed form elastic continuum solution by Einstein & Schwartz (1979) as modified by Carranza-Torres et al. (2013). The RINGS algorithm calculates the effective stress state around the tunnel perimeter. These calculated stresses are then transformed into equivalent earth loads that account for the load transfer mechanisms between the ground and the PCTL.

The equations for obtaining EV and EH for this case are as follows

$$\sigma'_{lining}(\theta) = (1 - \lambda(\theta)) \cdot \sigma'_{r,RINGS}(\theta) - P'_{SHIELD}(\theta); \lambda(\theta) = 1 - \frac{\sigma'_{r,RINGS}(\theta)}{\sigma'_{r,0}(\theta)} \quad (3)$$

$$EV = \frac{\sigma'_{lining}(0^\circ) + \sigma'_{lining}(180^\circ)}{2}; EH = K_{TBM} \cdot EV \quad (4)$$

For obtaining a single stiffness value the minimum elastic (unload-reload) modulus around the excavated radius is used: $E = \min \{E_{ur}(\theta, \sigma'_{r,RINGS}(\theta, r_0))\}$.

This approach is sufficient in many cases for obtaining the lining demands and utilization required by the design codes for a single tunnel. However, it cannot accommodate for construction of adjacent structures, consolidation or complex stratigraphy. In addition, the surface deformations must be calculated separately using empirical methods using the calculated volume loss.

3.3 Approach 2: Multi-Stage Non-linear 2D Soil-Structure Numerical Model

This approach is implemented here through numerical model in Bentley Plaxis2D. To provide a similar response to the MCSH, the standard HS model is used with $OCR = 2$ (to limit the isotropic hardening), while setting $K_0 = K_{nc}$.

The first stage involves applying the calculated stress reduction factor by RINGS to represent the ground state immediately after shield passage. In Plaxis2D the M-stage approach is used with no internal TBM pressure which requires calculation of a stress relaxation factor:

$$\lambda_{RINGS} = 1 - \frac{\bar{P}}{P_0} \quad (5)$$

where: $P_0 = (\sigma'_{v0} + \sigma'_{h0})/2 + WA$, $\bar{P} = (EV + EH)/2 + WA$. By adding WA, Equation 5 uses total stress rather than the effective stresses used in Approach 1. While this formulation can theoretically lead to lower EH values in cases of low K_0 and high relaxation, our experience has shown that the total stress approach is more robust when coupled with sensitivity checks on K_{TBM} .

This is followed by a second stage where $\sum M_{stage} = 1$ and the PCTL is activated and begins to interact with the surrounding ground. When using this approach, we recommend modelling the lining using solid elements (as opposed to 1D beams) as this allows for the correct diameter to which load is applied (i.e. extrados). The backfill grout is explicitly modelled as an elastic material filling the annular gap. The model also accounts for surface buildings and soil stratigraphy.

This unfactored analysis approach allows for the direct calculation of structural forces and moments in the lining, to which partial safety factors on the effect of actions are subsequently applied according to design standards. The primary advantage of this method lies in its ability to design the lining while accommodating for multiple excavations, obtaining ground movements and assessing the impact of tunnelling on adjacent structures and infrastructure in one model.

4 CASE HISTORY – FRANKFURT U5 METRO EXTENSION

The Frankfurt U5 metro extension project (Schade, et al., 2023; Rauch, et al., 2024) involved the construction of twin shallow tunnels with an excavated diameter of 7.1 m using reinforced PCTL with a thickness of 450mm. The TBM operations were conducted using an EPB machine at depths ranging from 12 to 20 m below ground surface through predominantly cohesive Frankfurt Clay formation.

The project monitoring program included a tunnel section at stationing 679m with direct monitoring of the lining demands using strain gauges. The well-documented soil and TBM operational parameters, make it a good case study for demonstrating the application of the ADCM for lining design.

4.1 Back-analysis Model Setup and Input Parameters

The model setup for Approach 1 and 2 is provided in Figure 3 below. The numerical model geometry closely matches the actual conditions at the monitored section and includes basements from existing multi-storey buildings and pressures assuming 12kPa per level, which equates to the soil loading from street level.

A review of the available documentation was carried to derive the required parameters for the ADCM back-analysis and summarized in Table 1 to 3 below. The data was taken directly from the factual data available which included TBM and tunnel geometry, HS soil parameters, TBM face pressures, advanced rate, and monitoring of surface settlements and PCTL forces. The grouting pressures were evaluated based on the water pressure and advanced rate (Zhong, et al., 2011).

Table 1. Back analysis tunnel geometry and TBM parameters at springline.

Tunnel Depth (m)	Water Depth (m)	D _{exc} (m)	D _{ext} (m)	D _{int} (m)	Shield Gap (mm)	P _{face} (bar)	P _{grout} (bar)	P _{SHIELD} (bar)	λ _{TBM} (θ = 0°)
15.75	15.75	7.1	6.8	5.9	25	2.5	3.25	2.9	0.47

Table 2. Back analysis MCSH soil parameters

Layer	γ (kN/m ³)	c' (kPa)	φ	ν	E ₅₀ ^{ref} (MPa)	E _{ur} ^{ref} (MPa)	p' _{ref} (kPa)	m	K ₀	K _a	K _{TBM}
Frankfurt Clay	18	20	25	0.2	35	105	100	1	0.57-0.74	0.49	0.57
Sand	21	0	35	0.2	50	125	100	1	0.43	0.27	NA

Table 3. Back analysis PCTL parameters

Thickness (mm)	Stiffness (GPa)	ν
450	36	0.25

The back-analysis was carried out both unfactored and to demonstrate how to implement partial loading factors using the two analysis approaches presented above. A design partial factor $\gamma_p = 1.35$ was adopted on EV + WA, EH + WA (Approach 1) or lining forces (Approach 2) in accordance with LRFDTUN-1.

4.2 Back-Analysis Results

Figure 4 gives the distribution of the measured lining demands compared to the ADCM factored and unfactored back analysis.

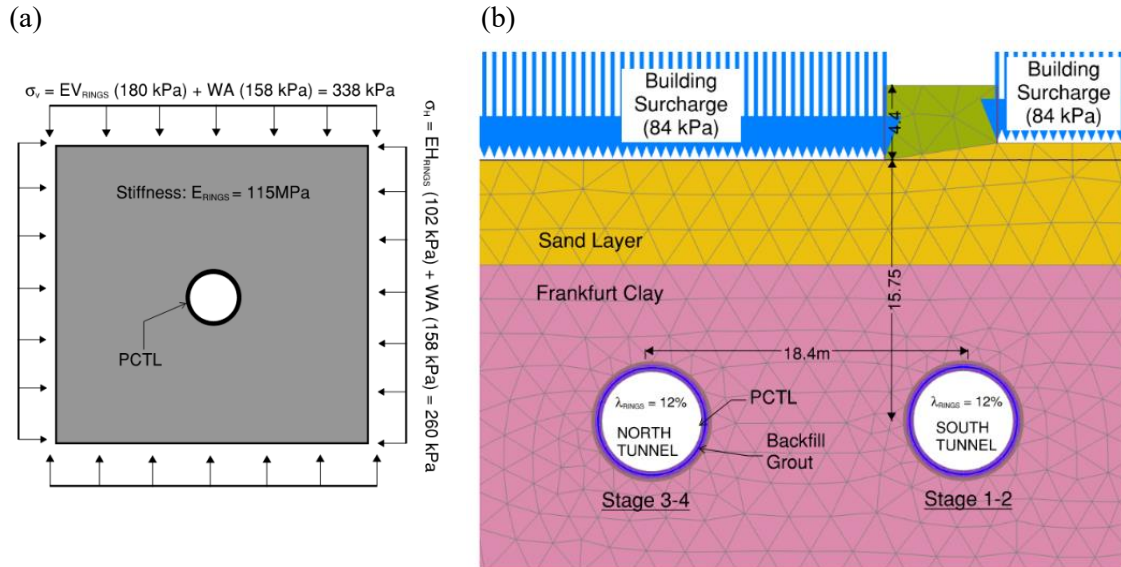


Figure 2. Model setup for back-analysis of the Frankfurt U5 PCTL monitoring section. (a) Approach 1: Continuum elastic analytical solution for a single tunnel (Carranza-Torres, et al., 2013) with the ground loads and stiffness obtained from the RINGS algorithm (b) Approach 2: Plaxis2D plastic analysis with gravity, soil stratigraphy, building surcharge and sequential construction of the South (first) and North (second) tunnels.

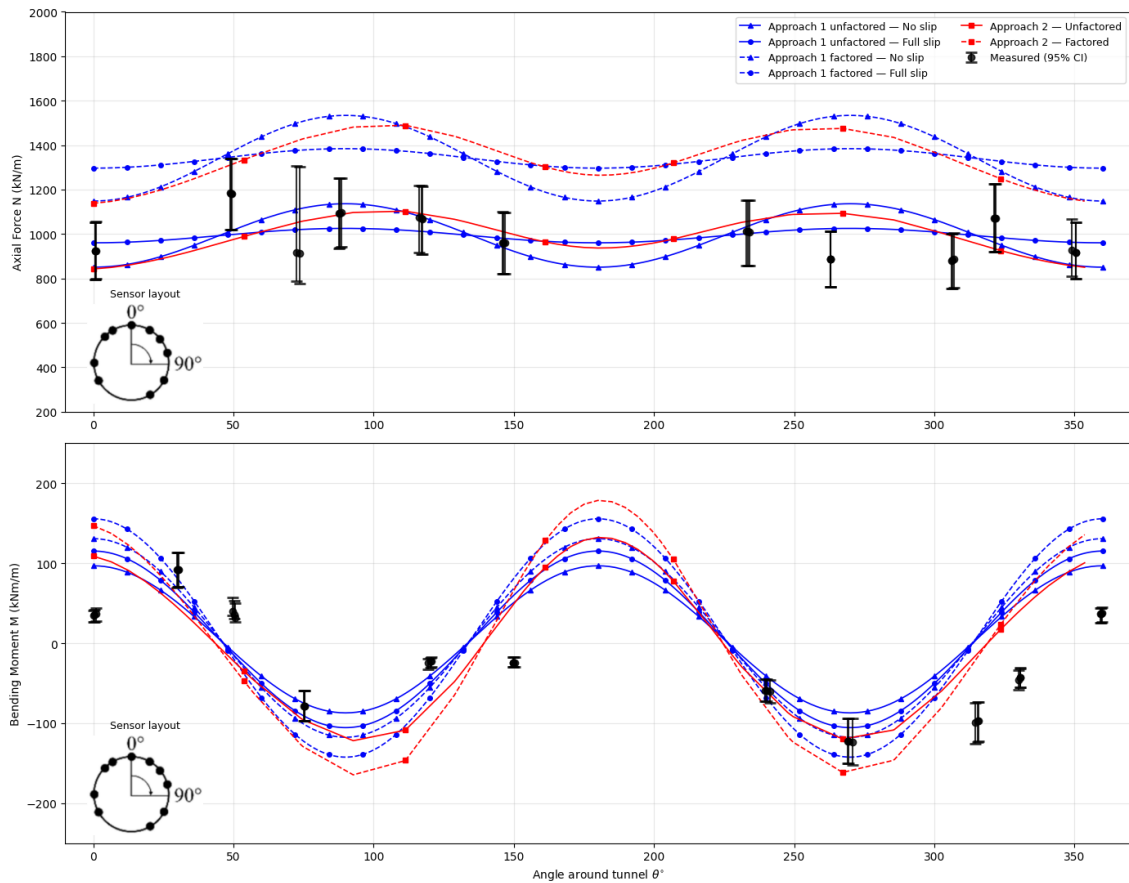


Figure 3. Comparison of the ADCM lining analysis approaches and the monitoring data. The measured values, sensor position and error margins are taken from Rauch et al (2024).

In addition to the lining demands, the ADCM calculates a small ground loss of 0.06% giving surface settlement of 1mm for each tunnel using empirical solutions for each tunnel (i.e. total of

2mm). The same settlement is obtained in the Plaxis2D analysis followed by a small heave during the lining installation phase. Available settlement monitoring data from the project owner (SBEV) 30m away from the study section, shows total movements of about 2mm per tunnel.

4.3 Discussion

4.3.1 Lining Demands

The unfactored (service) back-analysis provides a very reasonable match to the measured results for both axial force and moments that are within the margin of measured error and follow the same distribution. The factored (strength) results envelope the monitoring data. The measured bending moments at the right-hand side of the tunnel (left in the figure) fit the calculated results better than the opposite side. Rauch et al. (2024) attributed these moment irregularities to imperfections in the tunnel segmental ring, which is certainly a reasonable explanation.

The error compared to the measurements between the simple analytical (Approach 1) and fully numerical (Approach 2) are similar. In addition, the two separate analysis approaches give the same response when considering both boundary cases of the analytical solution. The no-slip case matches the numerical results better for hoop force, while the full-slip case matches the moments.

4.3.2 Ground Movements

The small movements calculated and observed (1-2mm) are normally within the tolerance of the surface monitoring system and therefore do not justify an elaborate discussion and interpretation. It is sufficient to say that both analysis and measurements show negligible surface movements.

The correlation between the TBM pressures and surface settlement can be used for setting settlement trigger levels during the tunnel drive which are also linked to the lining demands in the following way:

1. Higher TBM pressures will result in higher overall ground loads on the lining and reduced settlements. These higher loads generally increase the hoop forces and jacking forces.
2. Lower TBM pressures generally result in higher settlements and loads leading to reduced hoop forces.

The effect on the bending moments is dependent on the relationship between the ground stress and stiffness which are both a function of the level of relaxation. For many urban tunnels, the governing static lining design case will be of low hoop forces coupled with reduced ground stiffness, and so the trigger levels for the lining and surface settlements will coincide.

5 CONCLUSIONS

This paper presents how the ADCM links TBM controls and ground conditions to lining design in a fast and simple workflow. The strength of the method was demonstrated via back analysis of direct measurements of lining forces in a soft ground mechanized shield project. The good match to measured lining demands presented was achieved with two strikingly different methods:

1. A simple 2D analytical solution with the stiffness and unfactored and factored loads obtained directly from the novel RINGS and SHIELD algorithms.
2. A rigorous 2D soil-structure interaction numerical model using an advanced soil model for which the global ground relaxation (or stress reduction factor) is obtained from the same algorithms.

The method is scoped to short-term behaviour under closed-face conditions and typical uniform ground; escalation to full 3D numerical modelling remains appropriate for inherently three-dimensional situations (cross passages, station / shaft / portal interfaces, strong layering etc). Within that scope, the workflow is envisaged as design verification and live-decision making tool, which is quick to run, easy to iterate, and aligned with day-to-day design decisions and construction back-analysis.

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