Calibrating a 3D Finite Element Model of TBM Excavation Using Monitoring Data Through Bayesian Approaches

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13/10/2023

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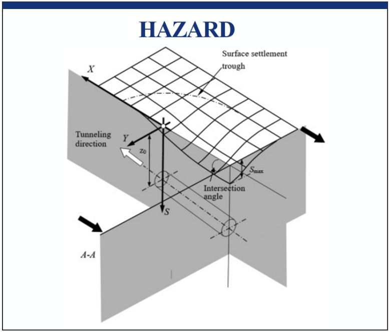
Tunnel Construction Risks

Key Question: Do tunnel constructions pose risks to people and property on the surface ?



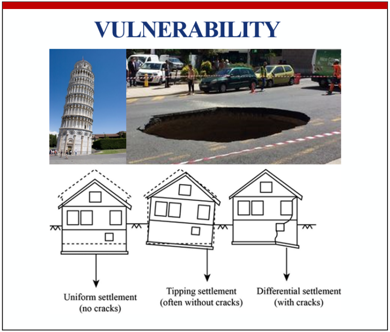


Figure: Surface Settlements (left) and "Fontis" observed during tramway construction in Nice (left)

TBM Earth Pressure Balance (EPB)

Tunnel Boring Machines (TBMs) are commonly used in shallow urban tunnel construction to **minimize soil displacement and mitigate risks effectively**

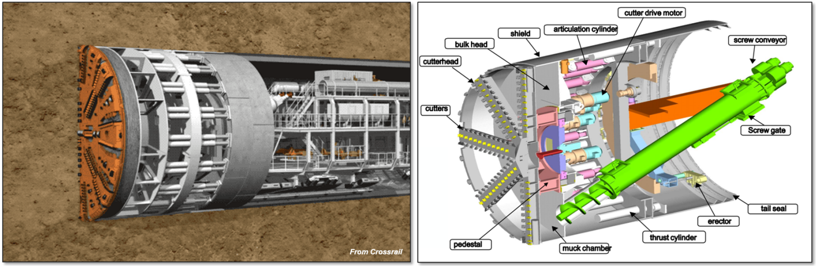


Figure: Tunnel Boring Machine - Earth Pressure Balance Technology

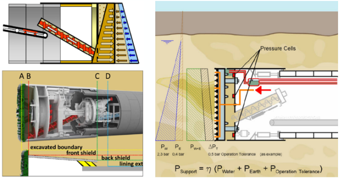
Factors Affecting Soil Displacement

Numerous factors influence soil displacement in shallow urban tunnel construction with TBM EPB

A Operational Factors

Driving Parameters : Face Pressure, Mortar Pressure, Excavation speed, Jack Pressure and Overexcavation

Design Parameters : TBM Conicity, Tunnel Radius, Tunnel Depth, …



B External Factors

Physical Parameters : Geological Properties, Water level and Soil Structure Interaction

Geometry Parameters : Surface Structures, Structures in Soil, …

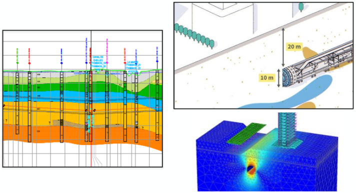


Figure: Factors Affecting Soil Settlements [8] [11]

Physical & Design Parameters

Case study: Segment of Metro Line 16 (approximately 5 km of track)

- **24** Geological Cross-Sections examined
- **2** Geometrical Parameters per Cross-Section
- **4** - 10 Geological Layers per Cross-Section
- **7** - **11** Mechanical Parameters per Geological Layer

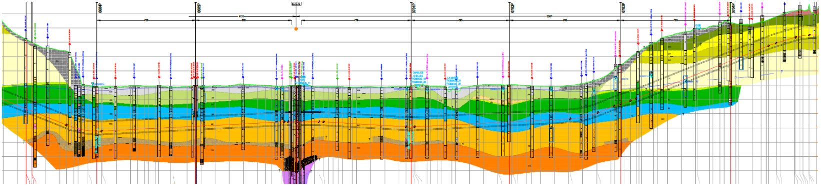


Figure: Metro Line 16 Geology Profile

Operational Factors

18 sensor values have been recorded from a sensor setup of 100 parameters on the TBM, with a 1 kHz frequency

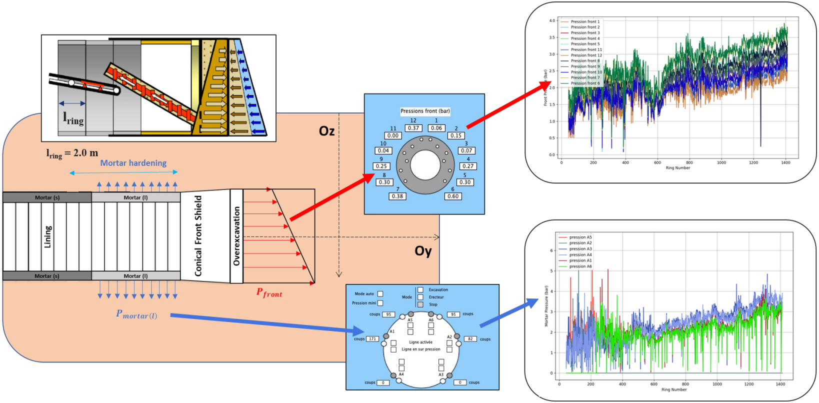


Figure: The Connection Between the Simulator and Measured TBM Driving Parameters

Surface Monitoring Data

In the study case, **880 road prisms** are monitored on average every **3 hours**

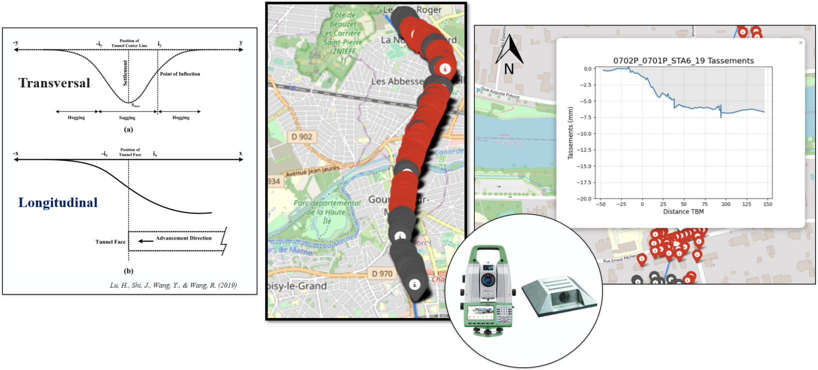


Figure: Illustration of Surface Monitoring Data

New Coordinate System

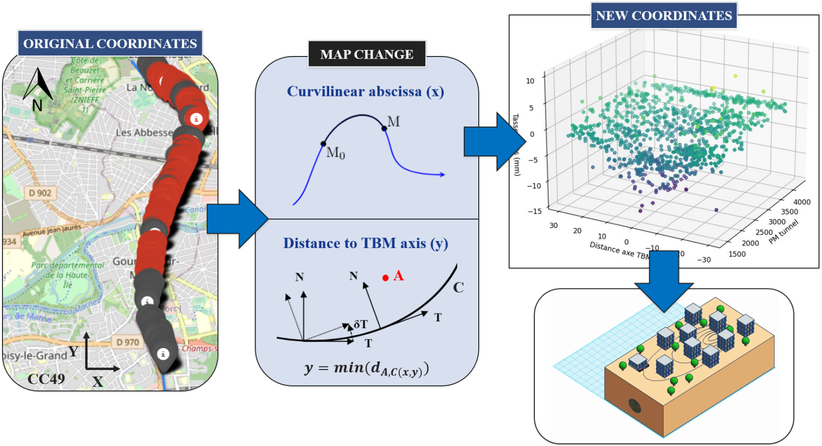


Figure: Process for Changing Map Coordinates

Mapping Settlements

Regressor model

$$z = \zeta(x') + \epsilon_\zeta \quad (1)$$

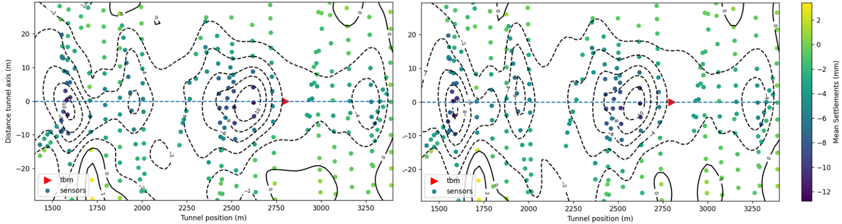
Assumptions made

- ζ as Gaussian Process: $GP(m(\cdot), c(\cdot,\cdot))$ [10]
- Matern Kernel ($\nu = 3/2$) for covariance function $c(\cdot,\cdot)$ (anisotropic)
- Constant mean function: $m(\cdot)$
- Gaussian Noise: $\epsilon' \sim N(0, \lambda)$
- Settlements z not time-dependent
- x': Position and distance on the tunnel axis (two-column table)
- Hyperparameters include kernel $(\rho_1, \rho_2, \sigma_0)$ and noise (λ)

Settlements Mapping

To **conduct this regression**, we employ different strategies:

- Choose the hyperparameters **manually** with "expert knowledge"
- **RELM algorithm** to find the optimal set of hyperparameters



Model	R^2	MAE	MSE	L_{inf}	ρ_1	ρ_2	σ_0^2	λ
Manual (left)	0.89	0.52	0.05	7.89	200	15.0	25.0	1.5
Auto (right)	0.87	0.55	0.05	8.76	135.5	20	6.4	1.1

PM = 2800

Figure: Regression Results (Python Library: gpmp [12])

How to Estimate Settlements?

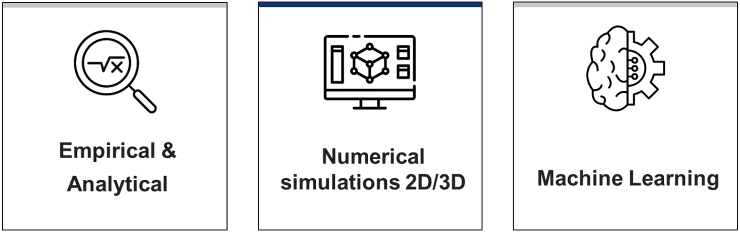


Figure: A Variety of Methods for Predicting Settlements [3][13]

To estimate tunnel settlements, a 3D parametric FEM for TBM excavation has been developed in Abaqus [1]

TBM Excavation Modelling

Various strategies can be employed to **model interactions between TBM and soil**

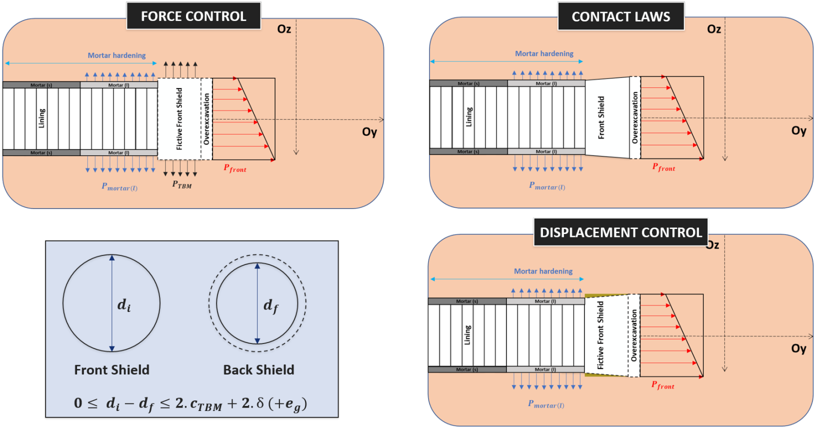


Figure: Different Strategies to model TBM excavation [5]

TBM Excavation Modelling

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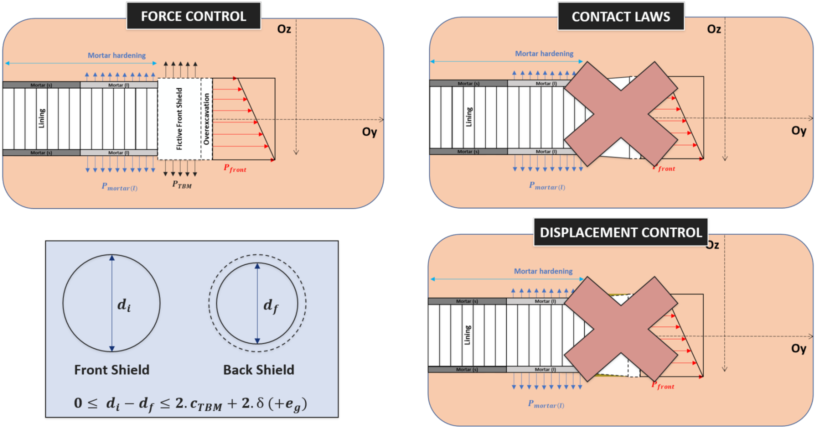

Figure: Different Strategies to model TBM excavation [5]

Geology Properties

Assumptions Regarding Geological Properties:

- Geological materials supposed elastic behaviour with the Mohr-Coulomb yield criterion
- Undrained Conditions (Total Stress) or Drained Conditions (Effective Stress)
- Water flow and water pressure in the soil are not taken into account
- K0 process for horizontal stress calcul, assuming horizontal layers

$$\sigma^{v}_{\text{eff}}(z) = \int_0^z \gamma_{\text{soil}}(l)\,dl - \int_0^z \gamma_{\text{water}}(l)\,dl \qquad (2)$$

$$\sigma^{v}_{\text{tot}}(z) = \int_0^z \gamma_{\text{soil}}(l)\,dl \qquad (3)$$

$$\sigma^{h}_{\text{x}}(z) = K_{0,x}(z).\sigma^{v}(z) \qquad (4)$$

$$\sigma^{h}_{\text{y}}(z) = K_{0,y}(z).\sigma^{v}(z) \qquad (5)$$

3D Finite Element Model of TBM Excavation

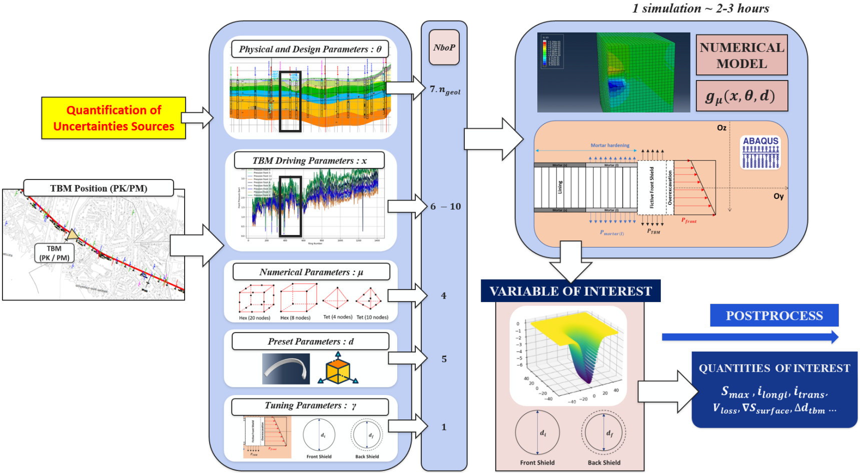

Figure: 3D Parametric Finite Element Model of EPB TBM Excavation[2][6][9]

Calibration Process

The calibration aims to **find optimal and acceptable** values for θ and γ that best fit the monitoring data

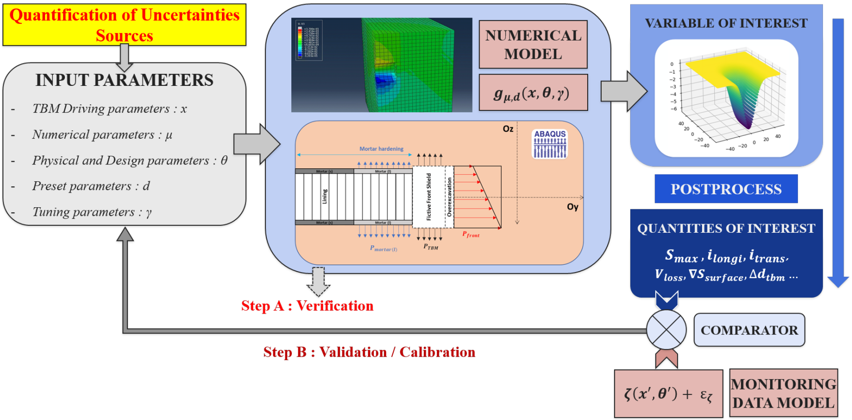

Figure: Objective of TBM Excavation Simulator Calibration [2]

BlackBox Model

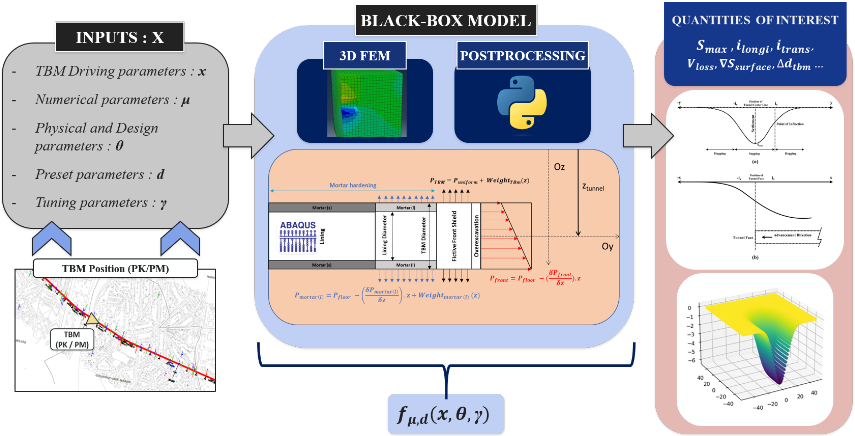

Figure: Modeling the TBM Excavation Simulator using a BlackBox approach

Surrogate Model

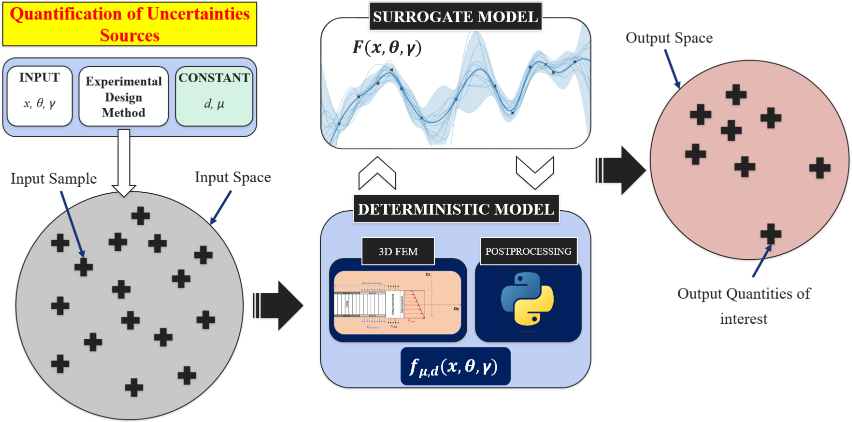

Figure: Surrogate Model of the TBM Excavation Simulator [2]

Before Calibration

Before initiating the calibration process:

- **Verify** simulation convergence for different input points
- **Manually validate** the model through comparisons with real data or established literature models, [6], following guidelines from organizations like CFMS [4]

The Calibration Problem can be formalized [2][7]

$$z = f_{\mu,d}(x, \theta, \gamma) + \epsilon \tag{6}$$

$$z = f_{\mu,d}(x, \theta, \gamma) + \delta(x) + \epsilon \tag{7}$$

Perspectives and Future Works

- **Last Manual Validation** of the TBM excavation model
- Complete **Quantification of Input Uncertainties**
- Implement Latin Hypercube Sampling (LHS) and **run multiple simulations** using high-performance computing
- Perform **Sensitivity Analysis** to reduce **Input Dimension**
- Develop a **Surrogate Model**
- Test **Bayesian Calibration Methods**

[1] G Abaqus. Abaqus 6.11. *Dassault Systemes Simulia Corporation, Providence, RI, USA*, page 3, 2011.

[2] Jean-Baptiste Blanchard, Rudy Chocat, Guillaume Damblin, Michaël Baudin, Nicolas Bousquet, Vincent Chabridon, Bertrand Iooss, Merlin Keller, Julien Pelamatti, and Roman Sueur. *Fiches pédagogiques sur le traitement des incertitudes dans les codes de calcul*. PhD thesis, EDF, 2023.

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[6] Michael Kavvadas, Dimitris Litsas, Ioannis Vazaios, and Petros Fortsakis. Development of a 3d finite element model for shield epb tunnelling. *Tunnelling and Underground Space Technology*, 65:22–34, 2017.

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[13] SM Yahya and RA Abdullah. A review on methods of predicting tunneling induced ground settlements. *Electronic Journal of Geotechnical Engineering*, 19:5813–5826, 2014.