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RANDOM FIELD-BASED TUNNELING INFORMATION MODELING FRAMEWORK FOR PROBABILISTIC SAFETY ASSESSMENT OF SHIELD TUNNELS

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Abstract. Probabilistic analysis based on random field (RF) has been widely adopted in the safety assessment of shield tunnels. However, its practical applicability has been limited by the intricacy involved with integrating geotechnical data and tunneling information. This paper addresses the following research question: How can the RF-based probabilistic safety assessment be carried out efficiently? In addressing this research question, we suggested an RF-based tunneling information modeling (TIM) framework to realize the probabilistic safety assessment of shield tunnels. In the proposed framework, the modeling of tunnel structure and geological conditions is initially introduced. The numerical safety assessment model is then created via an automated procedure using the RF-based TIM. A case study is conducted to verify the suggested framework, and results demonstrate that the framework can offer an automated design-to-analysis solution to improving the safety assessment of shield tunnels by comprehensively considering the uncertainties of geological conditions.

Keywords: safety assessment, shield tunnel, tunneling information modeling, random field.

Introduction

Shield tunnel excavation has been rapidly expanding around the world in response to the urgent need for underground space. For example, as of 2021, China has one of the most extensive metro systems in the world, with 244 lines totaling 7969.7 km in length (China Association of Metros, 2022). To ensure a safe shield tunnel excavation, a comprehensive safety assessment prior to the actual excavation is often needed due to the great uncertainties of underground condition (Chen et al., 2019; Hu et al., 2022). In current practice, numerical analysis is used to assess the safety level of shield tunnel design (Ninić et al., 2020). However, for many years, this analysis is completed by manually developing the simulation model, running the simulations, and evaluating the results, which is often time-consuming and error-prone (Ninić et al., 2017).

Building information modeling (BIM) has gradually improved interoperability between digital models and numerical simulations in the construction industry (Tang et al., 2020; Zhang et al., 2023b). BIM uses object-oriented parametric modeling to parse data from individual objects and use it in numerical simulations (Chen et al., 2015). Such a distinct characteristics of BIM have piqued the interest of the infrastructure sectors, leading to the expansion of BIM into civil information modeling (CIM), bridge information modeling (BrIM), and tunneling information modeling (TIM) (Sharafat et al., 2021). Recent studies have focused on the interoperability of TIM and numerical simulations (Fabozzi et al., 2021; Ninić et al., 2020). A fully automated design-through-analysis workflow has been devised that provides direct insight into the safety conditions via the digital model (Ninic et al., 2021).

Acknowledging the capabilities of TIM in numerical simulations, existing simulation methods from a geotechnical standpoint are deterministic analysis methods that cannot fully satisfy the safety assessment requirements due to the existence of soil property uncertainties. Uncertainties in soil properties are widely accepted as unavoidable and should not be overlooked in safety assessment (Li et al., 2021; Zhang et al., 2023a). The international society for soil mechanics and geotechnical engineering

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(ISSMGE-TC304, 2021) conducted an extensive review of inherent uncertainty in geotechnical engineering, noting that the properties of two soil samples tend to be more similar when the spatial distance between them is smaller. Such a spatial correlation structure with significant anisotropy can be described by an advanced formalism based on random field theory (RFT) (Vanmarcke, 2010). Given this issue, a probabilistic safety assessment (PSA) of shield tunnels that considers soil property uncertainties is preferable (Li et al., 2021; Shi et al., 2023; Zhang et al., 2022a).

However, the PSA is still limited due to the complexities of RFT and the tedious manual modeling process, raising an important research question "How can the RF-based probabilistic safety assessment of shield tunnels be carried out efficiently?". To answer this research question, three specific issues should be addressed: (1) coupling schema of soil property uncertainties and TIM; (2) automatic generation of random field (RF) based on TIM; and (3) dynamic generation and processing of PSA model. Consequently, this paper aims to develop an RF-based TIM framework to realize the PSA of shield tunnels. The subsequent sections of this paper are structured as follows. Section 1 initiates by introducing the methodology of the RF-based TIM framework. This section encompasses an in-depth discussion of the probabilistic analysis techniques employed in shield tunnel excavation and elucidates the methods for achieving seamless TIM-FEM interoperability. Moving forward, Section 2 delves into the detailed implementation of the RF-based TIM framework. In Section 3, a comprehensive case study is presented to assess and evaluate the performance of the proposed framework in a real-world scenario. The last two sections present the discussion and conclusions of this study.

1. Methodology of RF-based TIM framework

1.1. Probabilistic analysis of shield tunnel excavation

1.1.1. Uncertainties of soil properties

Geotechnical variability is a complex attribute due to the numerous sources of uncertainties. The inherent variability, for example, stems primarily from different depositional conditions and loading histories (see Figure 1) (Elkateb et al., 2003).

Soil properties have spatial correlation characteristics that cannot be adequately described by traditional one-point statistical parameters (e.g., the mean and coefficient of variation value) (El-Ramly et al., 2002). As a result, the Gaussian (squared exponential) correlation function can be used to represent the correlation between soil properties (Li et al., 2015):

$$\rho\left(\tau_x,\tau_y\right)=\exp\left[-\pi\left(\frac{\tau_x^2}{\delta_h^2}+\frac{\tau_y^2}{\delta_v^2}\right)\right], \qquad (1)$$

where ρ is the autocorrelation coefficient; τ_x and τ_y are the absolute distances between two points in the horizontal and vertical directions, respectively; δ_h and δ_v are the horizontal and vertical scales of fluctuations (SOFs), respectively.

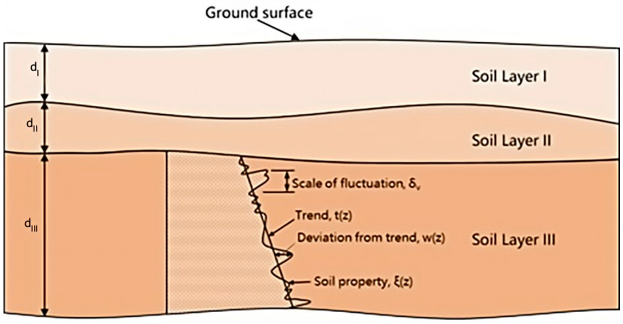

Figure 1. Inherent soil variability

In the existing literature, the spatial variabilities of soil properties are generally described by their correlation structure within the framework of RFs (Zhang et al., 2022c). RFT provides a solid framework for assessing soil spatial variabilities. The RFT framework employs location-specific dependence of soil properties, and soil properties within any given depositional unit are autocorrelated (ISSMGE-TC304, 2021). The RFs generation methods (e.g., spatial average method and spectral expansion method) are relatively mature, and the Karhunen-Loeve expansion method is one of the most widely-used methods because of its high accuracy and efficiency (Phoon et al., 2005). The detailed derivation process of the Karhunen-Level expansion method can be found in Xie et al. (2022). In this method, the random process $H(x, \theta)$ can be represented by the following expansion (Cho, 2010):

$$H\left(x,\theta\right)=\mu+\sum_{i=1}^{\infty}\sigma\sqrt{\lambda_i}\varphi_i\left(x\right)\chi_i\left(\theta\right), \quad x\in\Omega \qquad (2)$$

in which $\chi_i(\theta)$ symbolizes a set of orthogonal random coefficients (a set of independent standard normal random variables); $\theta \in \Theta$ is the coordinate in the outcome space; φ_i and λ_i are the eigenfunctions and eigenvalues of the autocorrelation function, respectively; and $\boldsymbol{x}$ is the coordinate of any point in the discrete space Ω, where Ω is an open set of R^n representing the system geometry.

Considering the efficiency and accuracy requirements, an approximate RF in the process of numerical simulation can be defined by truncating an ordered series, as follows (Liu et al., 2021a):

$$H\left(x,\theta\right)=\mu+\sum_{i=1}^{K}\sigma\sqrt{\lambda_i}\varphi_i\left(x\right)\chi_i\left(\theta\right), \quad x\in\Omega. \qquad (3)$$

To enhance computational efficiency, it is prudent to consider only the initial n terms. The determination of this n-value hinges on the ingenious concept of the ratio factor ε to meticulously gauge the calculation's accuracy in accordance with the specified criteria (Huang et al., 2001); this metric can be obtained based on Eqn (4). This intuitive metric bears witness to the trade-off between accuracy and computational cost, with a n-value nearing 1 signifying high accuracy but concurrently incurring a high computational expense:

$$\varepsilon = \sum_{i=1}^{n} \lambda_i / \sum_{i=1}^{\infty} \lambda_i . \quad (4)$$

Figure 2 depicts the RF configuration parameters of the Karhunen-Level expansion method for geotechnical properties, in which COV is coefficient of variation and ε is the ratio factor to assess the calculation accuracy based on the given requirements. The spatial correlation of soil properties can be characterized by the scale of fluctuation (Cami et al., 2020), which can be estimated from cone penetration test (CPT) data using methods such as and Bayesian analysis and maximum-likelihood estimation. It is worth noting that the distribution types most commonly employed to model soil properties encompass the normal distribution and the log-normal distribution.

1.1.2. Probabilistic analysis method

Probabilistic analysis of shield tunnel excavation has received increasing attention. One of the most robust probabilistic analysis methods is Monte Carlo simulation (MCS). This method enables the propagation of the uncertainties from the input data to the system output by a deterministic model, and the probability density function of the system response or the system failure probability can be correspondingly developed. Many safety assessment indicators have been adopted to assess the safety level of shield tunnel excavation (i.e., structural safety or serviceability) and tunneling-induced environmental impacts using probabilistic analysis methods, as illustrated in Figure 3. The failure probability P_f of shield tunnel excavation is expressed as follows (Li et al., 2013; Luo et al., 2018):

$$P_f \approx \frac{1}{n} \sum_{i=1}^{n} I_i \left(\delta \geq \delta_{\text{lim}} \right), \quad (5)$$

where n is the total number of samples in the MCS; δ is the predicted value of the evaluation indicators; I is an indicator function that returns a value of unity if $\delta \geq \delta_{lim}$ and returns zero if $\delta < \delta_{lim}$; δ_{lim} is the specified maximum allowable value of the evaluation indicators.

1.2. TIM-FEM interoperability framework

The interoperability of tunneling information modeling and finite element method (TIM-FEM) has been well studied in recent years (Fabozzi et al., 2021; Ninić et al., 2020; Ninic et al., 2021), and the geotechnical properties of the soil layers are among the most critical factors in the TIM-FEM interoperability framework. Geotechnical properties are generally determined through geotechnical investigation and can be used to create the geological model. In existing studies, geological models for numerical simulations are either simplified models where all soil layer interfaces are simplified as horizontal planes (Li et al., 2019; Lin et al., 2019), or realistic models based on sparse limited borehole data (Fabozzi et al., 2021; Zakhem & El Naggar, 2019; Zhang et al., 2022b; Zhang et al., 2021), as shown in Figure 4. Given that a simplified geological model cannot fully reflect the actual features of complex strata, a realistic geological model is preferable for a more detailed safety assessment (Fabozzi et al., 2021; Huang et al., 2022; Pan et al., 2020).

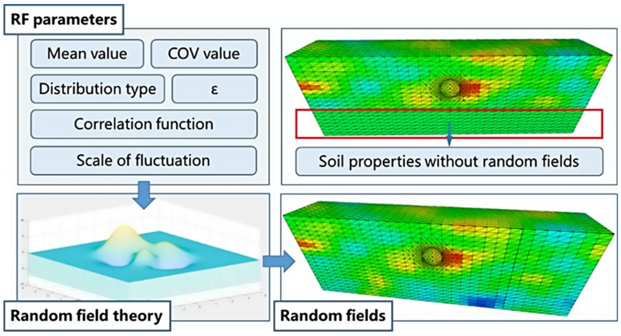

Figure 2. Generation of RFs for tunnel excavation based on Karhunen-Level expansion method

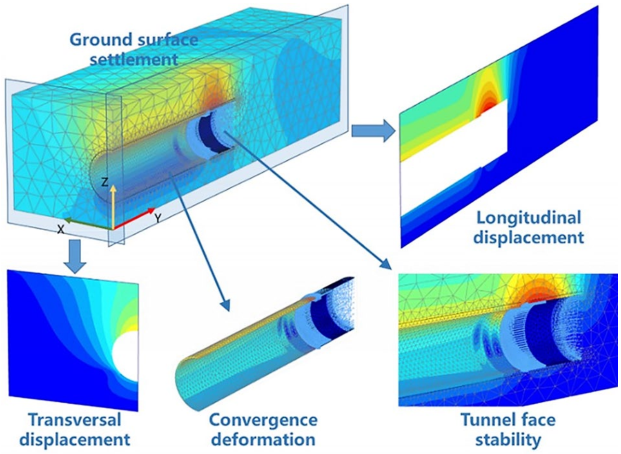

Figure 3. Common safety assessment indicators for tunnel excavation

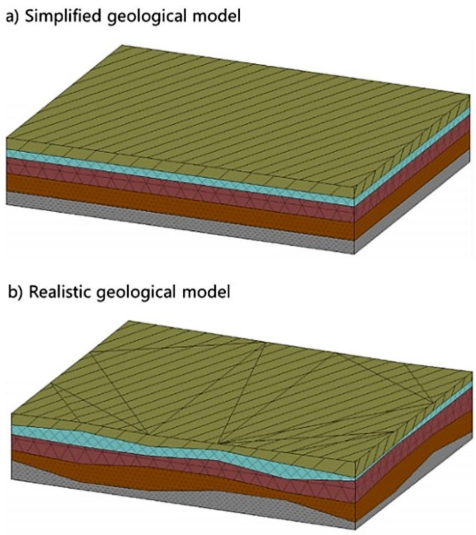

Figure 4. General geological models for numerical simulation: a – simplified geological model; b – realistic geological model

Parametric tunnel lining modeling is another critical component for TIM-FEM interoperability, and existing studies primarily used program scripts and predefined workflows to edit design rules and set parameters for tunnel lining modeling (Luo et al., 2022; Song et al., 2019; Wu et al., 2021a). These parametric modeling approaches for tunnel linings are oriented toward tunnel design or construction, which presents local geometric details. However, most numerical simulation processes do not strictly require a large LOD (level of details) of the tunnel lining model, and the tunnel lining structures can be simulated as uniform ring models (Kavvadas et al., 2017; Zheng et al., 2022). Furthermore, a large LOD of the tunnel lining model indicates a heavy computational load during the model transformation (Sharafat et al., 2021). Consequently, the generated tunnel lining model should have a proper LOD that neither affects the analysis accuracy nor increases the computational load. All these types of parameters should be considered in the TIM-FEM interoperability framework, upon which the PSA of shield tunnel excavation can be performed efficiently.

2. RF-based TIM framework

To recap, this paper aims to propose a novel RF-based TIM framework that includes: i) a TIM method that incorporates soil property uncertainties; ii) automatic and dynamic RF generation of tunneling information model in any arbitrary tunnel section; iii) automatic PSA process by using the tunneling information model. Figure 5 depicts the workflow of the proposed framework.

The TIM process encompasses several key components, primarily focusing on geological modeling, shield tunnel modeling, and shield machine modeling. This intricate procedure unfolds within the realms of both Dynamo and Revit platforms. The modeling process involves the creation of geometric entities and the subsequent assignment and linkage of relevant model parameters. These parameters span from the construction of geological entities, encompassing geotechnical and RF parameters, to the establishment of intricate relationships between the geometric entities and their associated parameters.

The automatic and dynamic RF generation process takes center stage, outlining a methodology for automatically determining the boundaries of the geometric model in numerical simulations. This determination is achieved through graphic methods, such as Boolean operations, applied to the selected shield tunnel sections. Subsequently, this process extends to the generation of the corresponding finite element mesh. It also devotes to the automatic acquisition of geological parameters and RF parameters from the geological model, facilitating the generation of RFs in a synchronized manner.

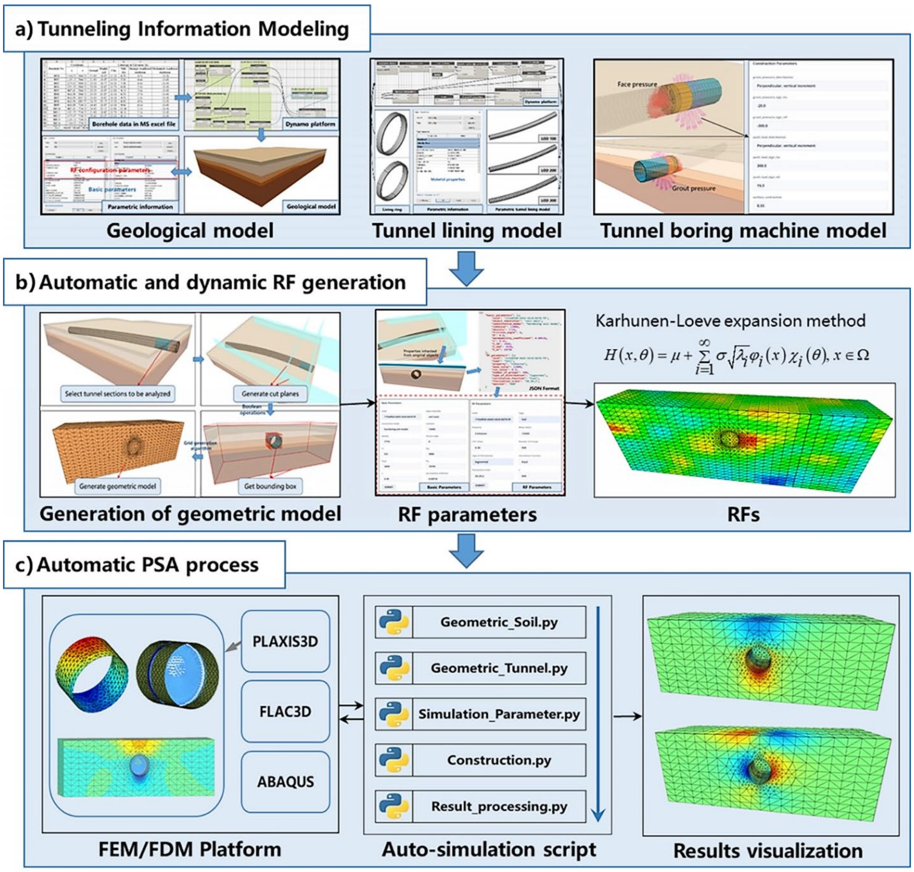

Figure 5. The workflow of RF-based TIM framework: a – tunneling information modeling; b – automatic and dynamic RF generation; c – automatic PSA process

The automatic PSA process mainly involves the integration of the generated RFs with their corresponding geometric models. Facilitated by a Python program, this step systematically retrieves all simulation-related model parameters, encompassing variables such as tunnel boring machine (TBM) operating parameters and shield segment material properties. As the culmination of this process, the Python interface is employed to initiate simulation work on the FEM/FDM platform. Subsequently, the system undertakes the analysis and visualization of the simulation results in an automated fashion, streamlining the overall workflow.

2.1. Tunneling information modeling

TIM is an object-oriented information expression method, in which engineering objects are made up of both geometric and non-geometric information (e.g., material properties and construction parameters). Generalized TIM typically includes the following elements: i) geological conditions, ii) shield tunnel lining, iii) TBM, iv) surrounding infrastructure, etc. In this study, the surrounding infrastructure is not considered in the proposed RF-based TIM framework. The following sections will cover parametric modeling of geological conditions, shield tunnel lining, and TBM.

2.1.1. Parametric geological model

To complete layered soil modeling, several algorithms such as kriging interpolation and Delaunay triangulation can be used. Taking Delaunay triangulation algorithm as an example, it triangulates the stratum surface of layered soil based on borehole data, and then encloses the stratum interface with boundary conditions to realize layered soil modeling. We present Dynamo, an Autodesk Revit visual programming platform, to realize the parametric modeling of geological conditions, as shown in Figure 6. The borehole data are first saved in Excel format before being used to create all stratum interfaces through functions of Topography.ByPoints and Topography.Mesh in Dynamo. Finally, a borehole-based stratified geological model can be created by using topological relations and interpolating the top and bottom depths of each soil layer. Each borehole-based soil layer is modeled using a generic model, and the soil properties obtained from the corresponding borehole data are attached to family-type properties in Autodesk Revit. Furthermore, the constitutive model and its corresponding model parameters use key-value pairs, which are fundamental data representations in an unordered list of unique attributes with associated values. The RF configuration parameters of soil properties are also linked to the family-type properties. These standardized forms of properties can be automatically retrieved for data exchange at the probabilistic analysis stage.

2.1.2. Tunnel lining model

The tunnel lining model can be generated by the centerline of the tunnel structure and local lining rings using Dynamo. An important issue in this process is to adopt a multiple LOD strategy in order to balance the computational load and evaluation accuracy for probabilistic analysis. To be more specific, the tunnel lining model with a large LOD (i.e., LOD 300) aids in the guidance of actual construction procedures, but the abundant model details will require significantly more computational resources when performing the RF-based probabilistic analysis. Instead, a model with moderate LODs (i.e., LOD 200) can be efficiently generated by parametric modeling and utilized in a web-based rendering platform because many local details are omitted. By selecting a pre-defined shield tunnel alignment, readily accessible within Autodesk Revit, one can generate a corresponding curve that accurately represents the tunnel's intended path. This curve can then be seamlessly integrated with the dimensions of the shield tunnel segments, allowing for the even distribution of these segments along the tunnel alignment. Subsequently, the shield tunnel segments can be precisely relocated to align with the segmented curve, culminating in the formation of the tunnel structure. Detailed instructions for executing these specific functions can be found in Figure 7.

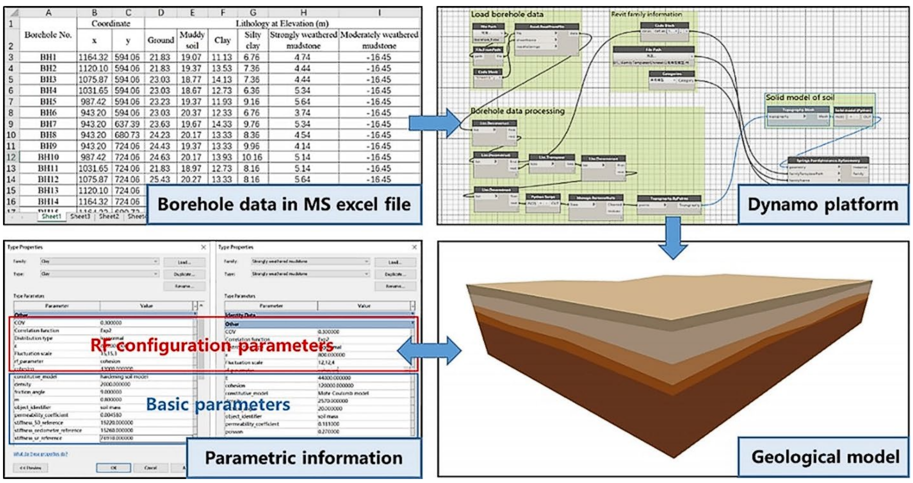

Figure 6. Parametric geological modeling in tunnel excavation using Dynamo and Revit platform

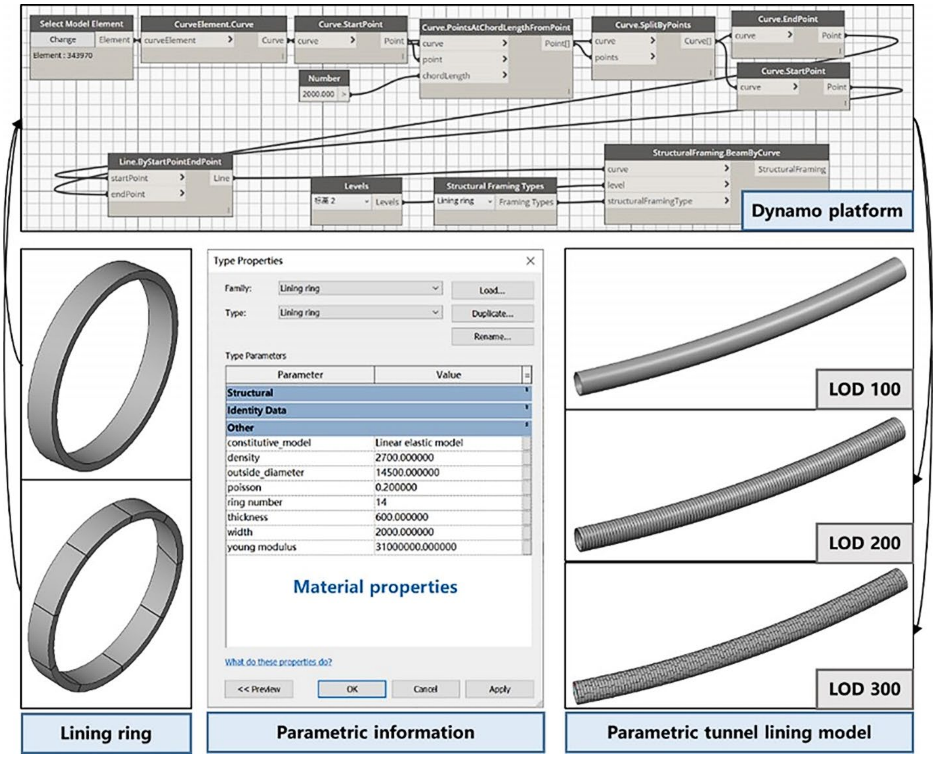

Figure 7. Parametric modeling of the tunnel lining model using Dynamo and Revit platform

After creating a tunnel lining model with multiple LODs, the corresponding constitutive model parameters are attached to the family-type properties of the model, and these parameters can be automatically retrieved for numerical simulations.

2.1.3. Tunnel boring machine (TBM) model

To realize the numerical simulation of shield tunnel excavation process, the information of construction sequence and construction parameters should be included in the tunneling information model. The construction of a shield tunnel can be divided into two distinct phases: tunneling and ring building. These two phases are performed alternately, and the construction parameters primarily involve grout pressure, tunnel face pressures, jack forces, surface contraction, and so on. Non-geometric information regarding the construction sequence and parameters can be obtained from the tunnel design schema or on-site monitoring. As shown in Figure 8, the spatiotemporal non-geometric information can be attached to the TBM model and retrieved for data exchange in numerical simulation. In this paper, the foremost focus revolves around non-geometric aspects of the TBM model, with particular attention given to factors such as face pressure, grouting pressure, and surface contraction. These critical parameters can seamlessly interface with the PLAXIS3D platform. The information regarding face pressure and grouting pressure mainly involves their distribution patterns, increments, and reference values. For a comprehensive understanding of these parameters, one can refer to the extensive documentation provided by PLAXIS. Moreover, surface contraction plays a pivotal role in replicating the soil volume reduction experienced during the construction of shield tunnels. The geometric model of TBM can be created by using modeling engine (e.g., Autodesk AutoCAD and Revit). The TBM model, along with the geological model and tunnel lining model, will serve the RF-based probabilistic analysis.

2.2. Automatic RF generation of tunneling information model

With technical details of TIM development in Section 2.1, the geometric information of tunneling information model can be extracted in OBJ format which is an open and universally recognized format for defining and storing geometric objects (Liu et al., 2021b). The non-geometric information of tunneling information model can be extracted in JavaScript Object Notation (JSON) format, allowing for structured data interchange using programming languages. Both types of information can be parsed and visualized by using the ThreeJS platform, which is the most widely used WebGL engine due to its openness and support for numerous 3D file formats such as stl, obj, fbx, etc. The following sub-sections will introduce the method of automatic RF generation of tunneling information model based on ThreeJS.

2.2.1. Generation of geometric model

RF-based probabilistic analysis method consumes a significant amount of computing resources. As a result, the 2D or local 3D model of shield tunnel has received special attention in order to reduce the computational load (Cho, 2010; Gong et al., 2018; Huang et al., 2017; Javankhoshdel & Bathurst, 2016; Luo et al., 2011). Considering the characteristics of tunnel excavation (i.e., tunneling phase and ring building phase alternately), a lining ring-based method is developed to generate the local 3D model from the tunneling information model. The proposed method allows design engineers to select individual tunnel sections to analyze and generate the cutting planes based on their spatial position of the selected sections. Using Boolean operations, the local 3D model is generated based on the cutting planes, and two bounding boxes are automatically built for the local geological model and tunnel lining model (see Figure 9). The spatial position and corresponding geometric information of the local geological model and tunnel model are obtained using bounding boxes. Then, the corresponding geometric model can be generated using the advancing front algorithm (Schöberl, 1997).

2.2.2. Confirmation of model parameters

Following the generation of the local 3D model, the corresponding properties of the generated objects will be inherited from their original models. As shown in Figure 10, these properties are stored and transferred in JSON. These properties are also linked to their geometric objects via a universally unique identifier (UUID) so that they can be easily retrieved by programming. To generate the RFs, design engineers must confirm the RF parameters for each object by referring to geotechnical investigation or commonly recommended values in related studies (see Figure 10). In the web-based interface of RF parameter configuration, the number of groups for PSA is also required to promote the MCS.

2.2.3. Automatic generation of random fields

To generate RFs for the geometric model, one of the most commonly used methods is to first extract the coordinates of the center point (RF point) of each mesh and subsequently generate RF for each mesh based on the spatial relationship of points and corresponding RF parameters. However, for complex strata surfaces, generating RFs for soil layers remains difficult due to uncertainties between the interfaces of different soil layers. Several key points

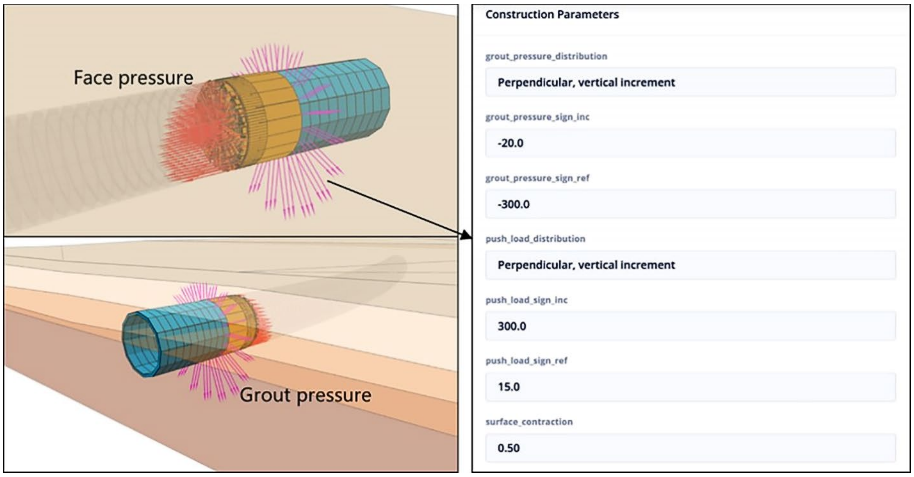

Figure 8. Geometric and non-geometric information of TBM

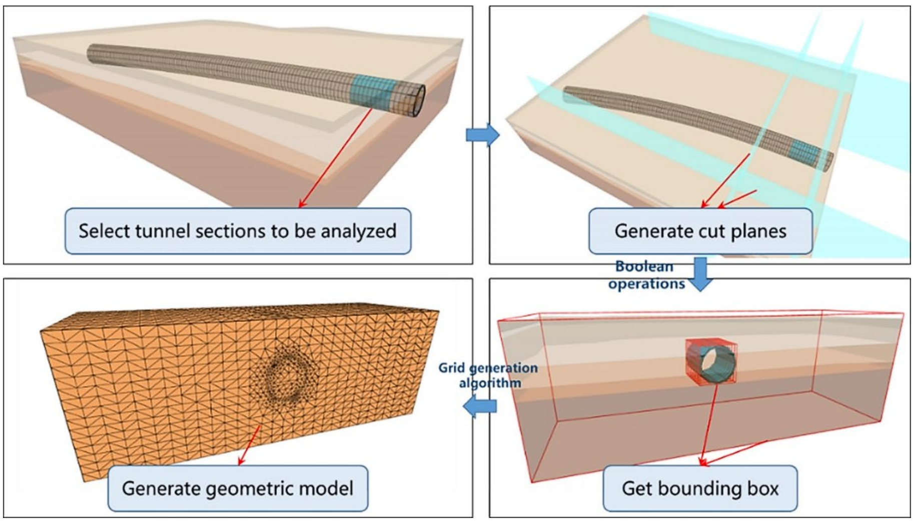

Figure 9. Generation of the geometric model for selected tunnel sections

should be considered when automatically generating RFs for complex soil layers, including: (1) paring and identifying the complex strata surfaces in a geometric model, which is used to match soil properties and generate the numerical model of strata; (2) classifying the center points of all meshes in the geometric model and determining the soil layer to which these points belong; (3) generating RFs for the classified points through their spatial relationship and corresponding RF parameters; (4) integrating generated RFs with the numerical model of shield tunnel excavation.

In light of the above considerations, an automatic RF generation method is proposed (see Figure 11). The geometric information of the complex strata surfaces in the tunnel information model is first exported in OBJ format (.obj). The geometry information in an OBJ file is essentially a polyhedron that is represented by vertices (points in 3D space) and faces (a convex polygon made by a list of vertices). Then, the coordinate of the center point (RF point) of each mesh is extracted and utilized to determine which soil layer the point belongs to. In this step, an efficient point in the polyhedron algorithm is adopted to

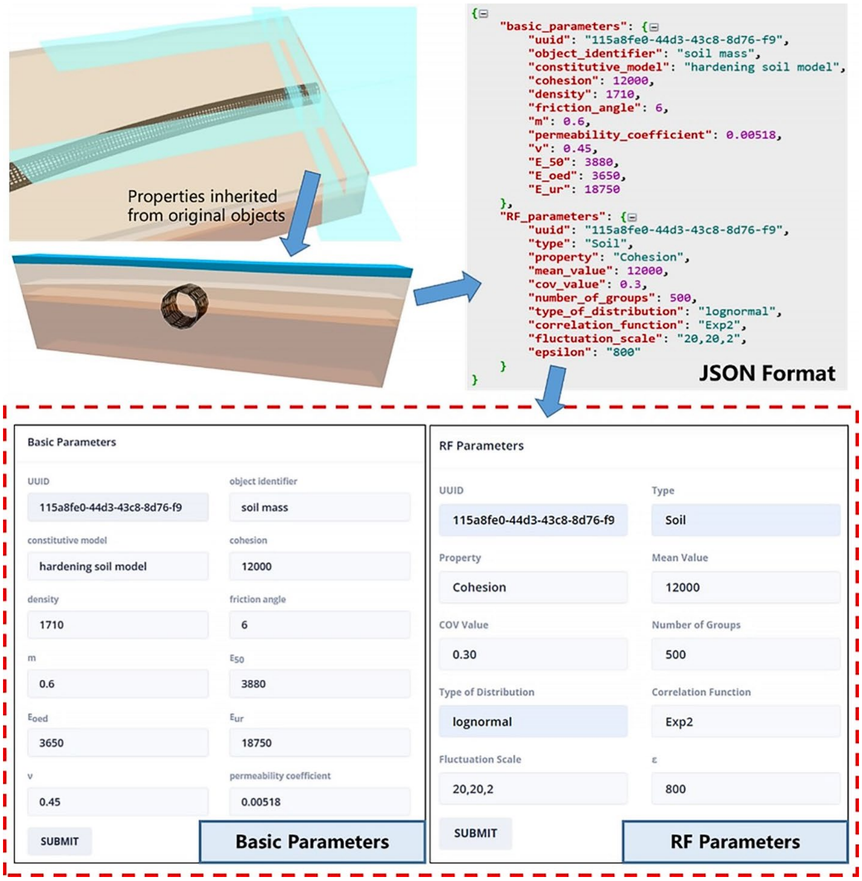

Figure 10. Configuration of model parameters and their transmission formats

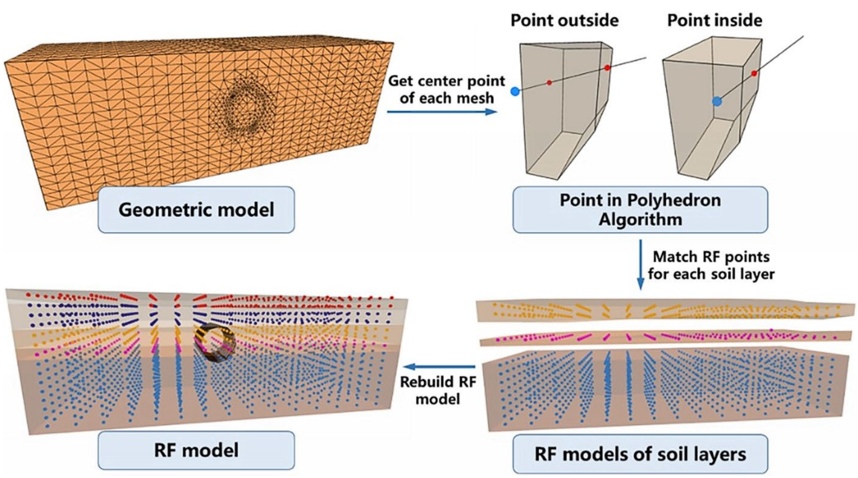

Figure 11. Generation of the RF model using point in polyhedron algorithm

determine the spatial relationship between the points and the polyhedrons. The "point in polyhedron" is a classic computer graphics problem. One solution to the problem is shooting a ray from the given point to an arbitrary direction and counting the numbers of intersections of the ray with the polyhedron. The given point is inside the polyhedron if the number of intersections is odd. Otherwise, it is outside the polyhedron.

After the center points of all meshes have been classified, RFs for the geometric model can be generated using the detailed workflow shown in Figure 12. The RF generator in this workflow is an application program (.exe) written in C++ language that introduces the Karhunen-Level expansion method to generate RFs, and readers can find the corresponding random field generation algorithm in Xie et al. (2022). The program can be called externally and receive incoming parameters such as RF parameters and coordinates of RF points. Through incoming parameters and RF generation algorithm, the RF generator can generate corresponding RFs (single soil layer) and pass them to the external handler, which regulates the generation of RFs in all soil layers.

2.3. Automatic simulation

With the development of numerical analysis software, many interfaces performed by Python or other scripting languages can be used to achieve automatic numerical simulation. For instance, the FLAC3D software package provides the FISH language, and the PLAXIS3D software package provides an operation interface; both allow users to manipulate the numerical model in a flexible manner. In this study, PLAXIS3D is adopted to automatically perform PSA using the Python scripting language. For shield tunnel excavation, the numerical simulation of the construction process mainly involves (1) performing the advance of a tunneling shield; (2) applying tunnel face pressures; and (3) applying grout pressure in the specifications of the tunnel construction process. These construction parameters are parsed and extracted from the TBM model. Figure 13 shows the detailed PSA process.

3. Case study

3.1. Case description

The RF-based TIM framework is implemented in a case project to validate its performance, as presented in Figure 14. In this case project, the tunnel lining is 14.5 m in outer diameter, 0.6 m thick, 2.0 m wide (see Figure 15a), and the tunnel depth is approximately 18 m. Based on the proposed TIM method in Section 2, Figure 15b presents the geological model with five layers of soil.

Based on the geotechnical investigation information of the tunnel project, the hardening soil (HS) model, which is an advanced model to simulate the behavior of soft soils (Schanz et al., 1999), is chosen to characterize the stress-strain behavior for soil layers ①–③ and Mohr-Coulomb (MC) model is chosen for soil layers ④ and ⑤. Table 1 displays the corresponding constitutive model parameters. In this case study, the spatial variabilities of soil cohesion and internal friction angle are adopted, and the corresponding RF parameters of these soil properties are presented in Table 2. According to the geological survey report, the groundwater level is located 16.6 m below the ground surface.

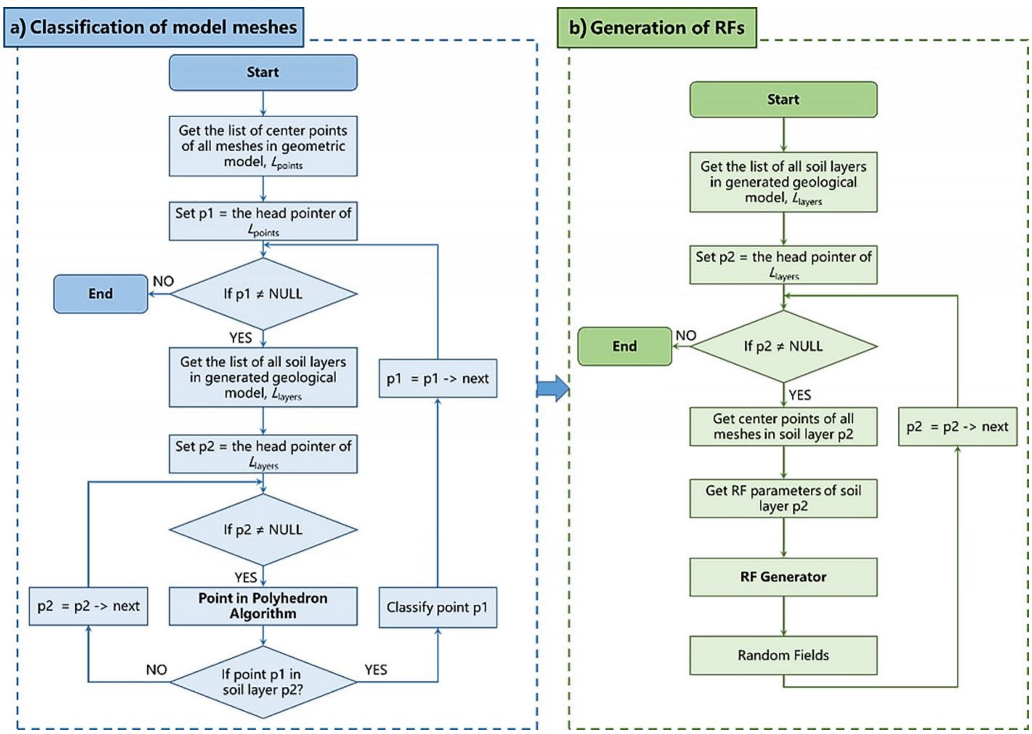

Figure 12. Automatic generation of random fields: a – classification of model meshes; b – generations of RFs

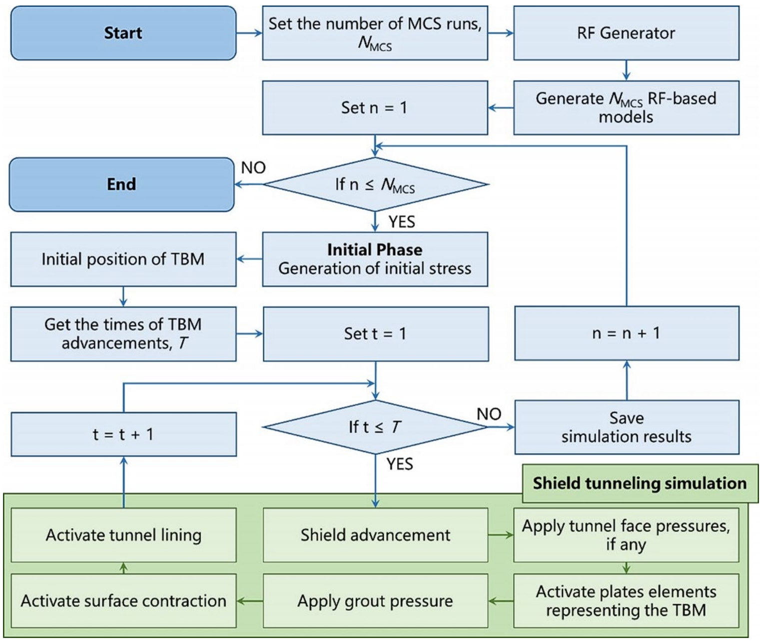

Figure 13. Automatic PSA process for shield tunneling simulation

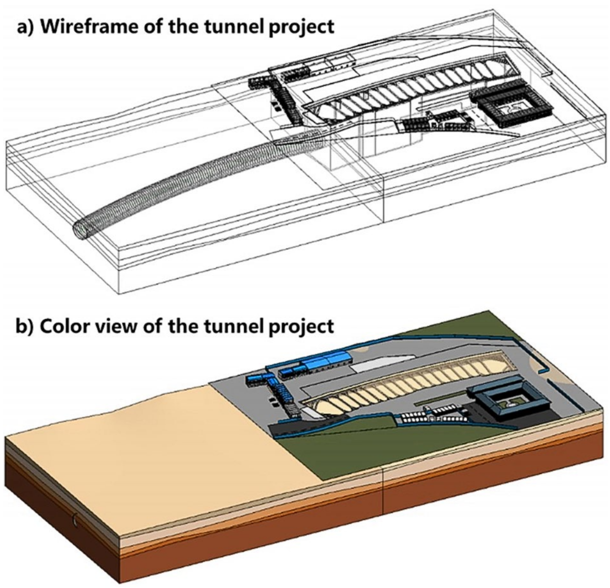

Figure 14. Overview of the case project: a – wireframe; b – color view

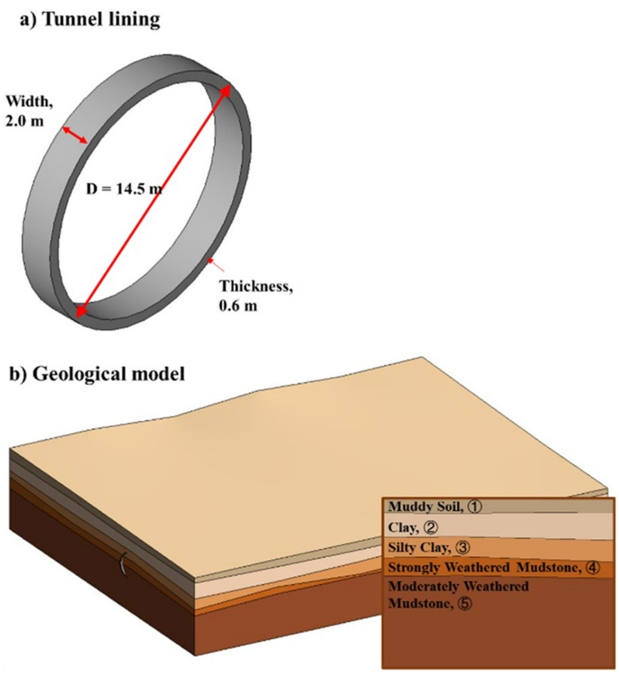

Figure 15. Parametric model of the project: a – tunnel lining; b – geological model

In the tunneling simulation, the surface load representing grout pressure is applied. The grout pressure is set to –300 kN/m^2 at the top of the tunnel and increased with –20 kN/m^2/m depth. The face pressure is set to –300 kN/m^2 at the top of the tunnel and increased with –15 kN/m^2/m depth. The surface contraction that represents ground loss due to tunnel excavation is set to C_{ref} = 0.5%.

3.2. Probabilistic safety assessment

Following the proposed RF-based TIM framework, the basic required parameters of engineering objects in shield tunnel excavation for numerical simulation are first extracted from the parametric tunneling information model. Following that, a geometric model of selected tunnel sections is created. With the assignment of RF parameters, the RFs of the geometric model are generated, and the PSA is performed automatically. As shown in Figure 16, once the required parameters of numerical simulation are prepared, the interface program of auto-simulation framework will make an asynchronous call and send the input parameters to the FEM/FDM software packages. A listener program is set up to record the generated result files, which are saved in a database. The use of an asynchro-

Table 1. Constitutive models and model parameters

Parameter	① Muddy soil	② Clay	③ Silty clay	④ Mudstone	⑤ Mudstone	Lining
Model	HS	HS	HS	MC	MC	Elastic
γ (kN/m^3)	17.10	20.00	20.00	25.7	25.7	25
c (kPa)	12	43	40	120	150	–
φ (°)	6	9	11	20	30	–
E_{50}^{ref} (kN/m^2)	3.88×10^3	19.22×10^3	21.05×10^3	–	–	–
E_{oed}^{ref} (kN/m^2)	3.65×10^3	15.26×10^3	16.32×10^3	–	–	–
E_{ur}^{ref} (kN/m^2)	18.75×10^3	76.91×10^3	84.21×10^3	–	–	–
k(m/day)	5.18×10^{-3}	8.64×10^{-3}	4.58×10^{-3}	1.81×10^{-1}	7.78×10^{-2}	–
m	0.6	0.8	0.8	–	–	–
ν	0.45	0.42	0.40	0.27	0.27	0.20
E (kN/m^2)	–	–	–	44×10^3	60×10^3	31×10^6

Table 2. RF parameters of soil properties

Soil layer	Mean		COV		Distribution type	Correlation function	Fluctuation scale		ε
	c (kPa)	φ (°)	c	φ			Horizontal	Vertical	
①	12	6	0.30	0.15	lognormal	Eqn (1)	20	2	800
②	43	9	0.30	0.20	lognormal	Eqn (1)	15	3	800
③	40	11	0.25	0.10	lognormal	Eqn (1)	15	3	800
④	120	20	0.30	0.20	lognormal	Eqn (1)	12	4	800
⑤	150	30	0.25	0.20	lognormal	Eqn(1)	10	4	800

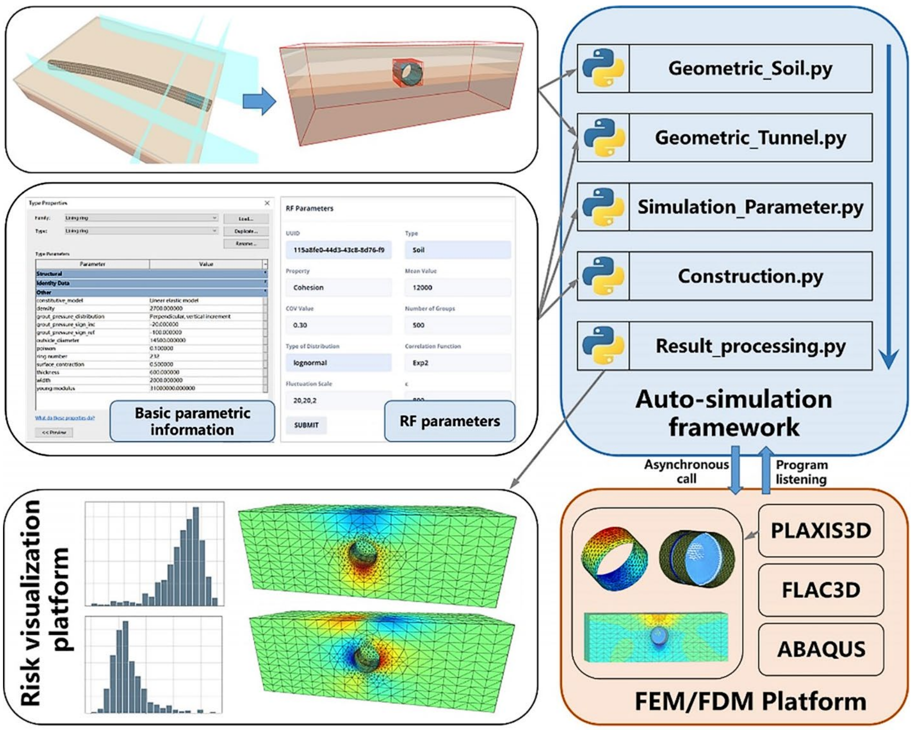

Figure 16. Detailed process of the PSA of shield tunnel excavation

nous call and listener allows to perform inter-module with high cohesion and low coupling. The boundary conditions automatically generated by PLAXIS3D according to the characteristics of the geometric model. The geometric size of this case project is about 120 m × 37 m × 39 m and the total number of model elements is 31056. Additionally, the numerical control parameters use default iter parameters in PLAXIS3D.

3.3. Evaluation results

For the numerical simulation of shield tunnel excavation, a group of indicators should be used in the PSA, which mainly involves the maximal settlement, soil displacement, convergence deformation of the tunnel lining, and tunnel face stability. In this case study, the maximal ground surface settlement and soil displacement are used as the PSA indicators, and the simulation is conducted at a workstation with a 2.40 GHz Quad-core CPU, and each MCS run takes about 10 minutes to complete. Figure 17 presents the contour plot of the simulation results from one of 1000 MCS runs.

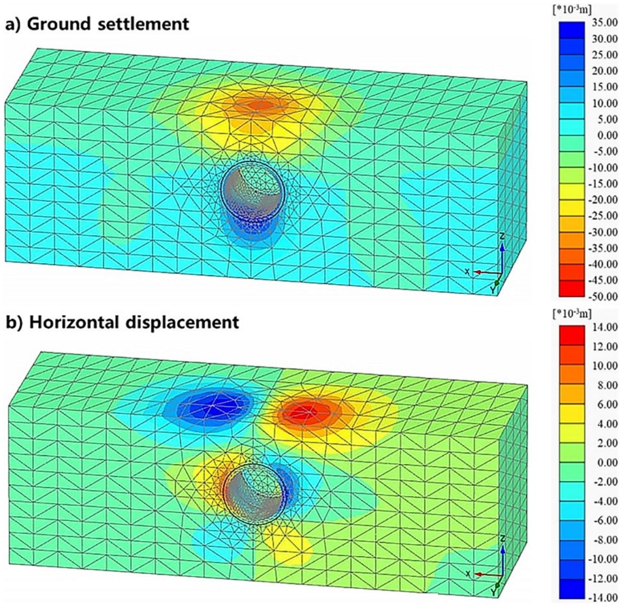

Figure 17. Contour plot of the simulation results:
a – ground settlement; b – horizontal displacement

The statistical analysis of ground surface settlements and soil displacements reveals that soil property uncertainties influence these two PSA indicators (see Figure 18). The impacts can be characterized by the range ratios (RR), and the results in Table 3 show that soil property uncertainties have a greater impact on soil horizontal displacement than on ground settlement. Such findings confirm that the uncertainties of soil properties are indeed important factors to consider in the safety assessment of shield tunnel excavation. Furthermore, the failure probability P_f of shield tunnel excavation can be determined by Eqn (5), and Figure 19 presents the curve of failure probability P_f changing with allowable value δ_{lim}, which provides theoretical support in the design stage. When we disregard the inherent uncertainty in soil properties, the current TIM-FEM framework yields maximum ground surface settlement and maximum horizontal displacement figures of 37.79 mm and 13.32 mm, respectively, as outcomes of shield tunnel construction. If we employ these results as the benchmarks, a comprehensive analysis utilizing the newly proposed RF-based TIM framework reveals that due to the unpredictability of soil properties, there exists a 49.1% probability of the maximum ground surface settlement and a 50.3% probability of the maximum horizontal displacement exceeding the previously established reference values. This underscores the fact that neglecting the uncertainty in soil properties can lead to a significant underestimation of construction risk. Therefore, it becomes imperative to incorporate considerations for soil property uncertainties when planning shield tunnel excavations.

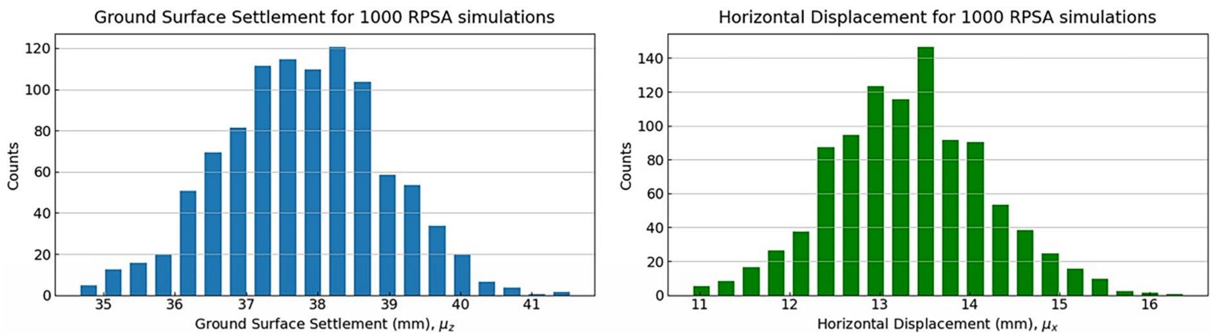

Figure 18. Statistical analysis of ground surface settlements and soil horizontal displacements

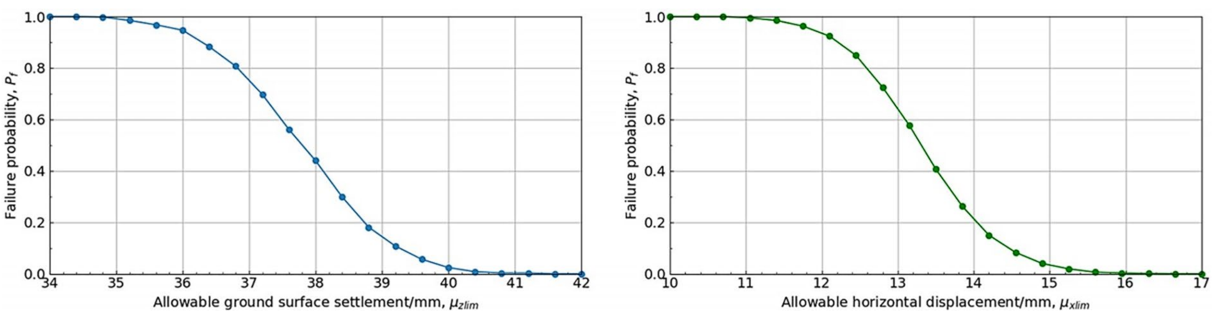

Figure 19. Curve of failure probability changing with allowable value

Table 3. Summary of the probabilistic analysis results

Indicator	S_{rmax} (mm)	S_{rmin} (mm)	RR	μ_{Smax} (mm)	COV_{Smax}
Ground surface settlement	41.588	34.613	1.201	37.787	0.030
Horizontal displacement	16.412	10.873	1.509	13.320	0.066

4. Discussion

To determine whether the assessment results are acceptable in the RF-based TIM framework, the stabilities of the results are evaluated based on their mean and COV values (Wu et al., 2021b). The converging trend of the assessment results of the case project is presented in Figure 20, demonstrating that 1000 MCS runs can produce stable results in both mean and COV values.

The proposed framework and current TIM-FEM integration approach are compared in order to further demonstrate the benefits of the proposed framework in safety assessment. The model parameters of the current TIM-FEM integration approach are derived from the basic parameters provided in Table 1, and the corresponding analysis results (red ground surface settlement curve) are shown in Figure 21. The simulation results of the proposed RF-based TIM framework that use 1000 sets of different random fields collectively form a range of ground surface settlement (a blue area in Figure 21). The comparison results show that the current TIM-FEM integration approach may underestimate potential safety risks during the shield tunneling process when soil property uncertainties are not considered. In contrast, the proposed framework can provide a more comprehensive safety assessment for the shield tunnel excavation, especially in areas where the soil properties are highly uncertain.

Despite its merits in advancing the use of probabilistic analysis in shield tunnel excavation, the RF-based TIM framework has limitations that remain to be addressed in the future.

Firstly, while the RF-based TIM framework is appropriate for conducting safety assessments over a predetermined time interval, it may not meet the need for real-time dynamic safety assessment, particularly when construction parameters are constantly changing. Consequently, the computational efficiency of the PSA can be improved by adopting parallel computing technology.

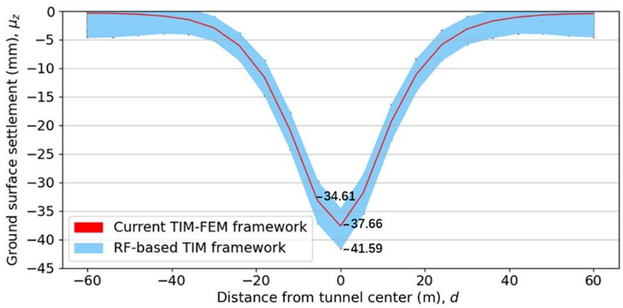

Figure 21. Comparison of the RF-based TIM framework and current method

Secondly, the RF-based TIM framework does not consider the effects of tunnel excavation on nearby infrastructure (e.g., building community, underground structure, etc.). Taking the adjacent building community as an example, tunneling-induced ground settlements may cause damage to these structures, but the characterization of building-soil interaction is still a challenge in the proposed framework. Consequently, a new parametric modeling or model processing strategy can be embodied into the proposed framework in order to balance the needs for computation efficiency, accuracy, and robustness.

Conclusions

Under the trend of digitalization of underground engineering, this study attempts to incorporate RF theory, numerical simulation approaches, and probabilistic/reliability theory into the tunneling information model of shield tunnel excavation. To address the challenges of comprehensive safety assessment that consider the great uncertainties of soil properties, a RF-based TIM framework is proposed that integrates TIM and RF theory to conduct probabilistic safety assessment. The main contributions of this study are summarized as follows:

(1) An RF-based TIM method is developed to rapidly model the shield tunnel excavation and efficiently integrate numerical modeling information, in which the parametric geological model can be automatically generated by limited borehole data and the parametric tunneling information model

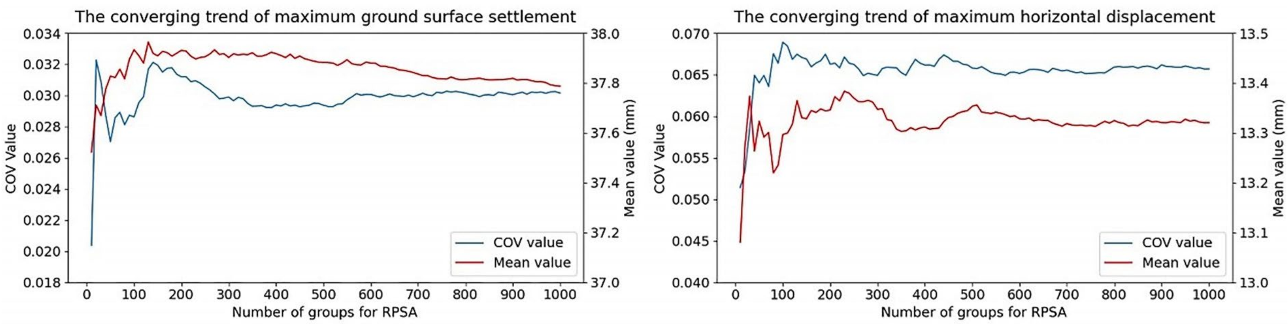

Figure 20. Converging trend of the assessment results

can be automatically built using a predefined tunnel axis and lining ring model;

(2) A lining ring-based method is proposed to generate the geometric models of numerical simulations from the parametric tunneling information model through ThreeJS. The bounding box algorithm and advancing front algorithm are implemented to generate the tunnel structure model and geological model for the probabilistic analysis, which can significantly improve the numerical modeling efficiency of shield tunnels;

(3) An automatic classification method of RF points based on "point in the polyhedron" algorithm is developed, which can be used to generate RFs for geological models with complex strata conditions. As a result, the geotechnical investigation information can be effectively used to reflect real geological conditions;

(4) An automatic simulation process is formulated to promote the probabilistic safety assessment of shield tunnel excavation, which can produce more comprehensive evaluation results than the current TIM-FEM integration approach.

Nomenclature

COV	Coefficient of variation
c	cohesion
E	Young's modulus
$E_{50}{}^{ref}$	secant stiffness in standard drained triaxial test
$E_{oed}{}^{ref}$	tangent stiffness for primary oedometer loading
$E_{ur}{}^{ref}$	unloading/reloading stiffness
HS	hardening soil
m	power for stress-level dependency of stiffness
MC	Mohr Coulomb
MCS	Monte Carlo simulation
PSA	probabilistic safety assessment
RF	random field
TIM	tunneling information modeling
ν	Poisson's ratio
φ	internal friction angle
ε	ratio factor to assess the accuracy of the random fields generation
γ	unit weight
k	permeability coefficient

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Author contributions

XP was responsible for Data curation, Visualization, Writing-Original draft preparation. HL was responsible for Project Administration, Supervision. KC was responsible for Conceptualization, Methodology, Writing-Reviewing and Editing, Supervision. YZ was responsible for Resources.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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